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Dynamic Aeroelastic Scaling of the CRM Wing via Multidisciplinary Optimization

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WCSMO12

Braunschweig, Germany
June 5, 2017

Introduction - Similarity and Optimization

Reference aircraft

Introduction - Similarity and Optimization

Reference aircraft

Scaled model

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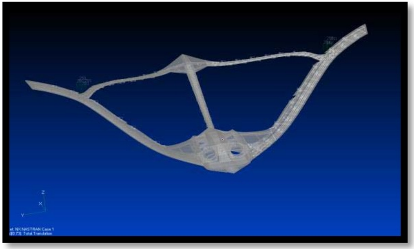
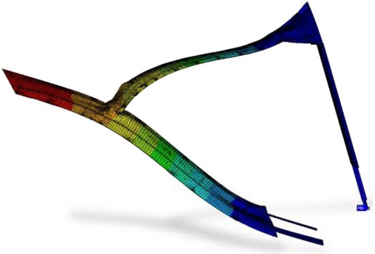
Introduction - Dynamic Aeroelastic Similarity



Reference aircraft mode shape*



Optimized scale demonstrator mode shape*

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

Outline

Tools

- Nastran 95*: Normal Modes and Flutter Analysis

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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]

Aeroelastic equations of motion:

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

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

Dynamic Aeroelastic Scaling

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Dynamic Aeroelastic Scaling

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[Ricciardi et al., Journal of Aircraft, 2014]

Adimensionalize with reference quantities:

$$\langle \bar{\mathbf{m}} \rangle \{\overset{\star\star}{\eta}\} + \langle \bar{\mathbf{m}}\bar{\omega}^2 \rangle \{\eta\} = \underbrace{\frac{V^2}{b^2\omega_1^2}}_{1/\kappa_1^2} \underbrace{\frac{gb}{V^2}}_{1/Fr^2} \langle \bar{\mathbf{m}} \rangle [\mathbf{\Phi}]^{-1} \{\bar{a}_g\}$$

$$+ \frac{1}{2} \underbrace{\frac{\rho S b}{m_1}}_{\mu_1} \underbrace{\frac{V^2}{\omega_1^2 b^2}}_{1/\kappa_1^2} \left([\bar{\mathbf{a}}_{\mathbf{k}}]\{\eta\} + \underbrace{\frac{\omega_1 b}{V}}_{\kappa_1} [\bar{\mathbf{a}}_{\mathbf{c}}]\{\overset{\star}{\eta}\} + \underbrace{\frac{\omega_1^2 b^2}{V^2}}_{\kappa_1^2} [\bar{\mathbf{a}}_{\mathbf{m}}]\{\overset{\star\star}{\eta}\} \right)$$

Traditional Dynamic Aeroelastic Scaling

Nondimensional aeroelastic equations of motion (harmonic solution):

Reference aircraft: r

Scaled model: m

$$\left\langle \bar{\mathbf{m}}_{\mathbf{r}} \right\rangle \{\overset{\star\star}{\eta}\} + \left\langle \bar{\mathbf{m}}_{\mathbf{r}} \bar{\omega}_{\mathbf{r}}^{\mathbf{2}} \right\rangle \{\eta\} = \frac{1}{2} \frac{\mu_{1r}}{\kappa_{1r}^2} [\bar{\mathbf{a}}_{\mathbf{hr}}(\mathrm{X}_{\mathrm{a}\mathbf{r}}, \kappa, \mathrm{M}_{\mathbf{r}})]\{\eta\}$$

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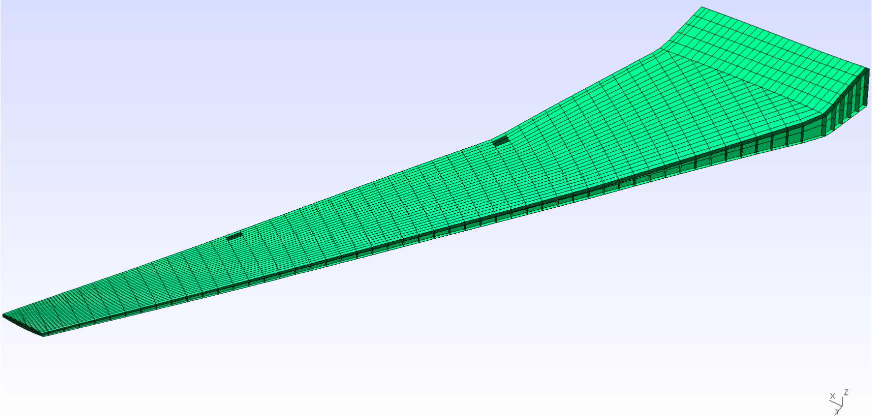
$$\overbrace{\langle \bar{\mathbf{m}}_{\mathbf{m}} \rangle \{\overset{\star\star}{\eta}\} + \langle \bar{\mathbf{m}}_{\mathbf{m}} \bar{\omega}_{\mathbf{m}}^{\mathbf{2}} \rangle}^{\text{Match } [\mathbf{\Phi}], \langle\bar{\omega}\rangle, \langle\bar{\mathbf{m}}\rangle \text{ (from the problem } K-\omega^2[\mathbf{M}]\{\phi\}=0) \text{ through optimization}}\{\eta\} = \frac{1}{2}\frac{\mu_{1m}}{\kappa_{1m}^2}\overbrace{[\bar{\mathbf{a}}_{\mathbf{hm}}(\mathrm{X}_{\mathrm{a}\mathbf{m}}, \kappa, \mathrm{M}_{\mathbf{m}})]}^{\text{Equal if same aerodynamic shape and flow similarity}}\{\eta\}$$

CRM Model

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

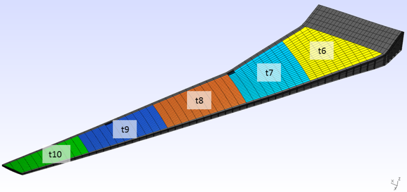


Model provided by T. Achard and C. Blondeau*

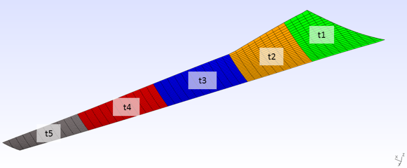
*[Achard et al., AIAA/ISSMO, 2016]

CRM modal optimization: Problem definition
Hypothesis: Flow similarity assumed

Objective Function		**Dimension**	**Bounds**
Mode shape difference minimization	$\min(N - \mathrm{trace}(\mathrm{MAC}([\Phi_r], [\Phi_m])))$	$\mathbb{R}$	
Design Variables			
Skin thicknesses vector	$[t]$	$\mathbb{R}^{10}$	$[0.0889, 26.67]$ mm
Constraints			
Reduced frequency matching	$\lVert\omega_r - \omega_m\rVert = 0$	$\mathbb{R}$	
Mass matching	$M_r - M_m = 0$	$\mathbb{R}$	
Generalized masses matching	$\lVert m_r - m_m\rVert = 0$	$\mathbb{R}$	

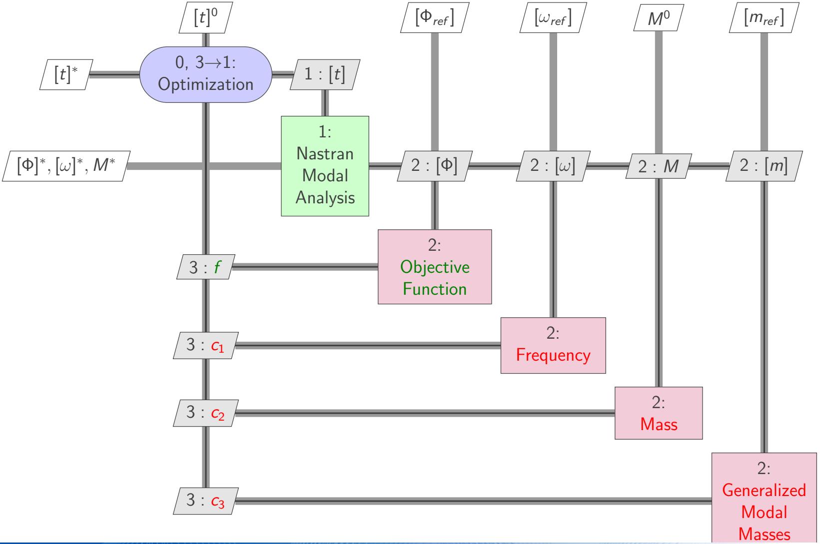


→ Upper skin panels



Lower skin panels ←

Traditional Modal Optimization
Hypothesis: Flow similarity assumed



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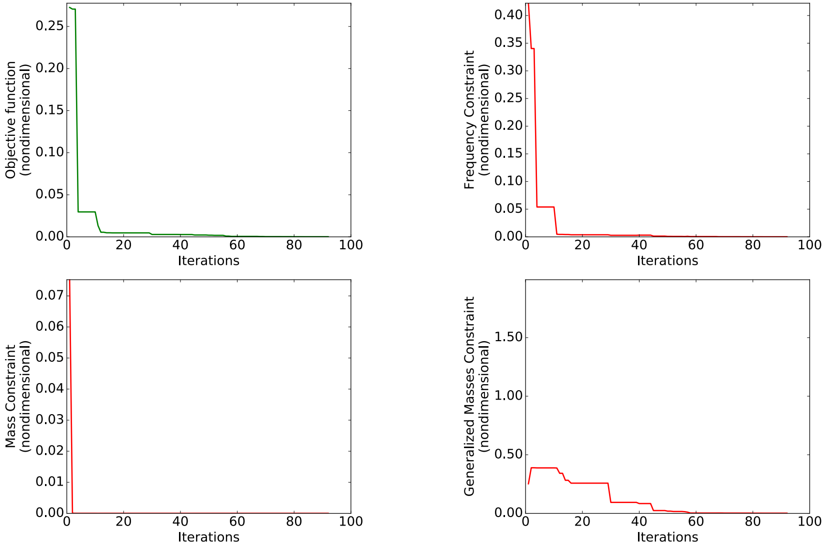
CRM Modal Optimization: Results
Best Found Point vs Iteration

Criterion: Point with best objective function AND sum of constraints



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What if the flow is not similar?

Reference aircraft: r

Scaled model: m

$$\langle \bar{\mathbf{m}}_\mathbf{r} \rangle \{\overset{\star\star}{\eta}\} + \langle \bar{\mathbf{m}}_\mathbf{r} \bar{\omega}_\mathbf{r}^2 \rangle \{\eta\} = \frac{1}{2} \frac{\mu_{1r}}{\kappa_{1r}^2} [\bar{\mathbf{a}}_\mathbf{hr}(\mathrm{X}_{\mathrm{a}\mathbf{r}}, \kappa, \mathrm{M}_\mathbf{r})] \{\eta\}$$

$$\langle \bar{\mathbf{m}}_\mathbf{m} \rangle \{\overset{\star\star}{\eta}\} + \langle \bar{\mathbf{m}}_\mathbf{m} \bar{\omega}_\mathbf{m}^2 \rangle \{\eta\} = \frac{1}{2} \frac{\mu_{1m}}{\kappa_{1m}^2} [\bar{\mathbf{a}}_\mathbf{hm}(\mathrm{X}_{\mathrm{a}\mathbf{m}}, \kappa, \mathrm{M}_\mathbf{m})] \{\eta\}$$

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$$\overbrace{\langle \bar{\mathbf{m}}_{\mathbf{m}} \rangle \{\overset{\star\star}{\eta}\} + \langle \bar{\mathbf{m}}_{\mathbf{m}} \bar{\omega}_{\mathbf{m}}^{\mathbf{2}} \rangle}^{\text{matched through modal optimization}}\{\eta\} = \frac{1}{2}\frac{\mu_{1m}}{\kappa_{1m}^2}\overbrace{[\bar{\mathbf{a}}_{\mathbf{hm}}(\mathrm{X}_{\mathbf{am}}, \kappa, \mathrm{M}_{\mathbf{m}})]}^{?}\{\eta\}$$

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What if the flow is not similar? Aerodynamic Optimization

- Reference aircraft: r
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Objective function:

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$$f = \sum_i \left(\left\| [\bar{\mathbf{a}}_{\mathbf{hr}}(\mathrm{X}_{\mathrm{a}\mathbf{r}}, \kappa_{\mathbf{i}}, \mathrm{M}_{\mathbf{r}})] - [\bar{\mathbf{a}}_{\mathbf{hm}}(\mathrm{X}_{\mathrm{a}\mathbf{m}}, \kappa_{\mathbf{i}}, \mathrm{M}_{\mathbf{m}})] \right\| \right)$$

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Design variables:

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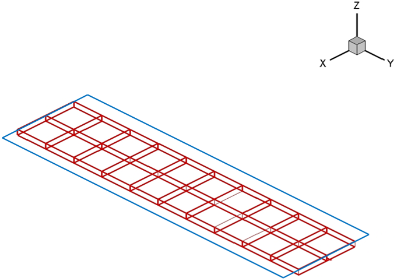
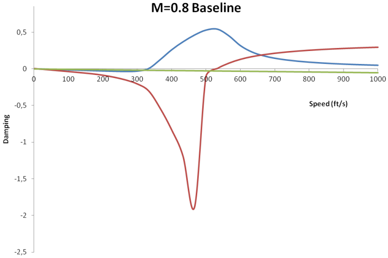
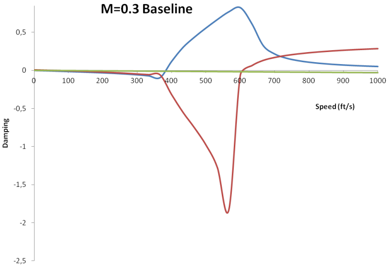
Design variables:

- $\mathrm{X}_{\mathrm{a}m}$: Parameters defining the wing planform

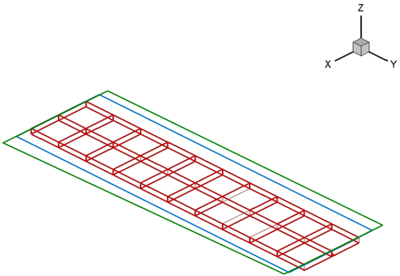
Aerodynamic Optimization: Goland Wing Test Case

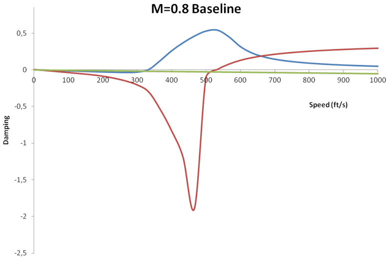


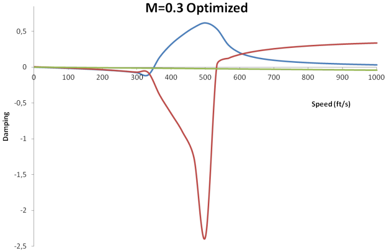




Aerodynamic Optimization: Goland Wing Test Case







Conclusion

- Review of the traditional dynamic aeroelastic scaling approach

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- Modal optimization for similarity

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- Wing planform optimization for flutter similarity

Perspectives

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

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- 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

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Thanks for your attention!

Questions?