Comparing the use of Aerodynamic Adjoint and Aeroelastic Adjoint in Aeroelastic Optimization of Industry-Relevant Aircraft Configuration

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With contributions by AIRBUS and ONERA
Overall Objective of MADELEINE

Demonstrate the **benefits of adjoint-based MDO**

The targets of the **Wing Design Package** in MADELEINE are to:

- Validate the implementation of the coupled aeroelastic adjoint approach
- Demonstrate the use of aeroelastic adjoint on industry relevant configurations
- Evaluate the benefit of the aeroelastic adjoint in wing optimization
  - Considering the accuracy
  - Considering the computational cost

**Topic of this talk**
Content of the Talk

- The coupled aeroelastic adjoint approach

- Investigating the benefit of employing the aeroelastic adjoint for different wing flexibilities

\[
\frac{\partial R_A}{\partial \bf w} \lambda_B = (\frac{\partial I}{\partial \bf w})^T - (\frac{\partial f}{\partial \bf w})^T Q^T \lambda_B^{k+1}
\]

\[
\bf Y^k = (\frac{\partial I}{\partial \bf x})^T - (\frac{\partial R_A}{\partial \bf x})^T \lambda_B^{k}
\]

\[
\bf K_M^A \lambda_M = \bf Y^k - (\frac{\partial f}{\partial \bf x})^T Q^T \lambda_B^{k+1}
\]

\[
\bf K_S^A \lambda_S = -Q \lambda_B^{k}
\]
The Coupled Aeroelastic Gradient

- **The Aerodynamic Gradient**

  The direction in which the aerodynamic functions (e.g. Drag coefficient) increase most quickly from current state

- **The Aeroelastc Gradient**

  The direction in which the aerodynamic functions (e.g. Drag coefficient) increase most quickly from current state *given the elasticity of the wing structure*
The Coupled Aeroelastic Gradient

- **Validating the gradients @DLR**
  - **The Aerodynamic Gradients**
  - **The Aeroelastic Gradients**
The Coupled Aeroelastic Gradient

- Validating the gradients among MADELEINE partners

Gradient Validation for $C_{D_p}$

- adjoint frozen $\nu$ (ONERA)
- adjoint SA lin. (ONERA)
- adjoint SA lin. (AIRBUS)
- adjoint SA lin. (DLR)

Common parameterization & CSM model
The Benefit of the Coupled Aeroelastic Gradient

- The first attempts, in MADELEINE, to compare engaging the aeroelastic adjoint versus the aerodynamic adjoint in shape optimization showed barely any benefit

*On the Benefits of Engaging Coupled-Adjoint to Perform High-Fidelity Multipoint Aircraft Shape Optimization, Romain Olivanti and Joël Brézillon, AIAA 2021-3072
The Benefit of the Coupled Aeroelastic Gradient

• The first attempts, in MADELEINE, to compare engaging the aeroelastic adjoint versus the aerodynamic adjoint in shape optimization showed barely any benefit.

• Starting from which wing structure stiffness does the use of coupled aeroelastic adjoint pay off?

**Idea of investigation:**

• Generate several CSM models by reducing the Young’s modulus (E) and the shear modulus (G) of elasticity simultaneously until the linear theory limits are reached.

• Use the resulting CSM models in the following optimizations:

  1. Compute the flight shape (CFD-CSM) for each suggested new shape and run the aerodynamic adjoint to compute the gradients and forward them to the optimizer (SQP).

  2. Compute the flight shape (CFD-CSM) for each suggested new shape and run the coupled aeroelastic adjoint to compute the gradients and forward them to the optimizer (SQP).
Investigating the Effects of Wing Flexibility on use of coupled Adjoint

- The AIRBUS XRF-1* configuration was employed for this investigation
- CSM model provided by DLR; Metal instead of CFRP, sized with a different set of loads
- Objective: improvement of Aerodynamic Efficiency (LoD) for a single flight point
- Parameterization employed was:
  - based on CAD-ROM,
  - engaging 126 profile design parameters (over 7 sections along span)

Investigating the Effects of Wing Flexibility on use of coupled Adjoint

- The CSM models

E & G 100% (of values of baseline CSM model) \( \delta Z/b = 6.50\% \)
Investigating the Effects of Wing Flexibility on use of coupled Adjoint

- The CSM models

E & G 100% (of values of baseline CSM model)  \( \delta Z/b = 6.50\% \)
E & G 80%  \( \delta Z/b = 7.65\% \)
Investigating the Effects of Wing Flexibility on use of coupled Adjoint

- The CSM models

E & G 100% (of values of baseline CSM model) \( \delta Z/b = 6.50\% \)
E & G 80% \( \delta Z/b = 7.65\% \)
E & G 70% \( \delta Z/b = 8.34\% \)
Investigating the Effects of Wing Flexibility on use of coupled Adjoint

- The CSM models

  E & G 100% (of values of baseline CSM model) \( \delta Z/b = 6.50\% \)
  E & G 80\% \( \delta Z/b = 7.65\% \)
  E & G 70\% \( \delta Z/b = 8.34\% \)
  E & G 60\% \( \delta Z/b = 9.22\% \)
Investigating the Effects of Wing Flexibility on use of coupled Adjoint

- **The CSM models**

| E & G 100\% (of values of baseline CSM model) | $\delta Z/b = 6.50\%$ |
| E & G 80\% | $\delta Z/b = 7.65\%$ |
| E & G 70\% | $\delta Z/b = 8.34\%$ |
| E & G 60\% | $\delta Z/b = 9.22\%$ |
| E & G 50\% | $\delta Z/b = 10.3\%$ |

Wing tip deformation ~10\% half span $\rightarrow$ **linear theory limits reached**
Investigating the Effects of Wing Flexibility on use of coupled Adjoint Optimization Chain

Optimizer  \(\rightarrow\) Design variables

- CFD
- Engine
- CSM

Cruise Performance

States & Gradients

RANS-corrected DLM

CSM

Loads & Structure Sizing

Overall Aircraft Design

ROM-based OAD Constraints
Investigating the Effects of Wing Flexibility on use of coupled Adjoint

Optimization Results: 100% of E&G, $\delta Z/b = 6.50\%$

Both optimizations reach similar value of the objective
Investigating the Effects of Wing Flexibility on use of coupled Adjoint

Optimization Results  80% of E&G, $\delta Z/b = 7.65$

- Restart the aeroelastic adjoint based optimization while employing the aerodynamic adjoint.
Investigating the Effects of Wing Flexibility on use of coupled Adjoint

**Optimization Results**  
70% of E&G, $\delta Z/b = 8.34\%$
Investigating the Effects of Wing Flexibility on use of coupled Adjoint

Optimization Results – 60% of E&G, $\delta Z/b = 9.22$

- Restart the aeroelastic adjoint based optimization while employing the aerodynamic adjoint
  - No improvement obtained
Investigating the Effects of Wing Flexibility on use of coupled Adjoint

Optimization Results  60% of E&G, $\delta Z/b = 9.22$

- Restart the aeroelastic adjoint based optimization while employing the aerodynamic adjoint
  - No improvement obtained

- Restart the aerodynamic adjoint based optimization while employing the aeroelastic adjoint
  - Some improvement was obtained
Investigating the Effects of Wing Flexibility on use of coupled Adjoint

Optimization Results — 50% of E&G, $\delta Z/b = 10.3\%$
Conclusions

- The coupled aeroelastic adjoint was implemented, validated among partners and its use was demonstrated.

- First trends showed that the benefit of the coupled adjoint appears starting from values of $\delta Z/b \sim 8\%$.
  - To be able to conclude, these investigations should be done for different configurations and with different optimization algorithms.

- More studies are required to investigate the benefit obtained vs. the computational cost.
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