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**

CM3

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MADELEINE project,
Grant Agreement No 769025

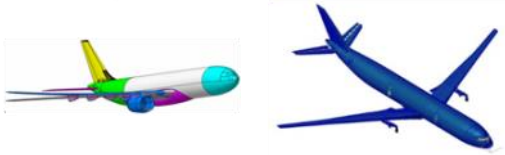
Overall Objective of MADELEINE

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

Airframe

Wing/fuselage aero-structure interactions

Aerodynamics ⟷ *Structure*



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

$$
\begin{aligned}
\left(\frac{\partial \mathbf{R}_A}{\partial \mathbf{w}}\right)^T \lambda_A^k &= \left(\frac{\partial I}{\partial \mathbf{w}}\right)^T - \left(\frac{\partial \mathbf{f}}{\partial \mathbf{w}}\right)^T \mathbf{Q}^T \lambda_S^{k-1} \\
\mathbf{Y}^k &= \left(\frac{\partial I}{\partial \mathbf{x}}\right)^T - \left(\frac{\partial \mathbf{R}_A}{\partial \mathbf{x}}\right)^T \lambda_A^k \\
\mathbf{K}_M^T \lambda_M^k &= \mathbf{Y}^k - \left(\frac{\partial \mathbf{f}}{\partial \mathbf{x}}\right)^T \mathbf{Q}^T \lambda_S^{k-1} \\
\mathbf{K}_S^T \lambda_S^k &= -\mathbf{Q}\, \lambda_M^k
\end{aligned}
$$

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

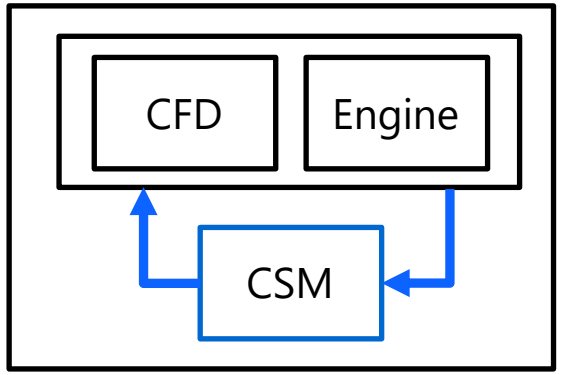
The Coupled Aeroelastic Gradient

- The Aerodynamic Gradient

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

- The Aeroelastic 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

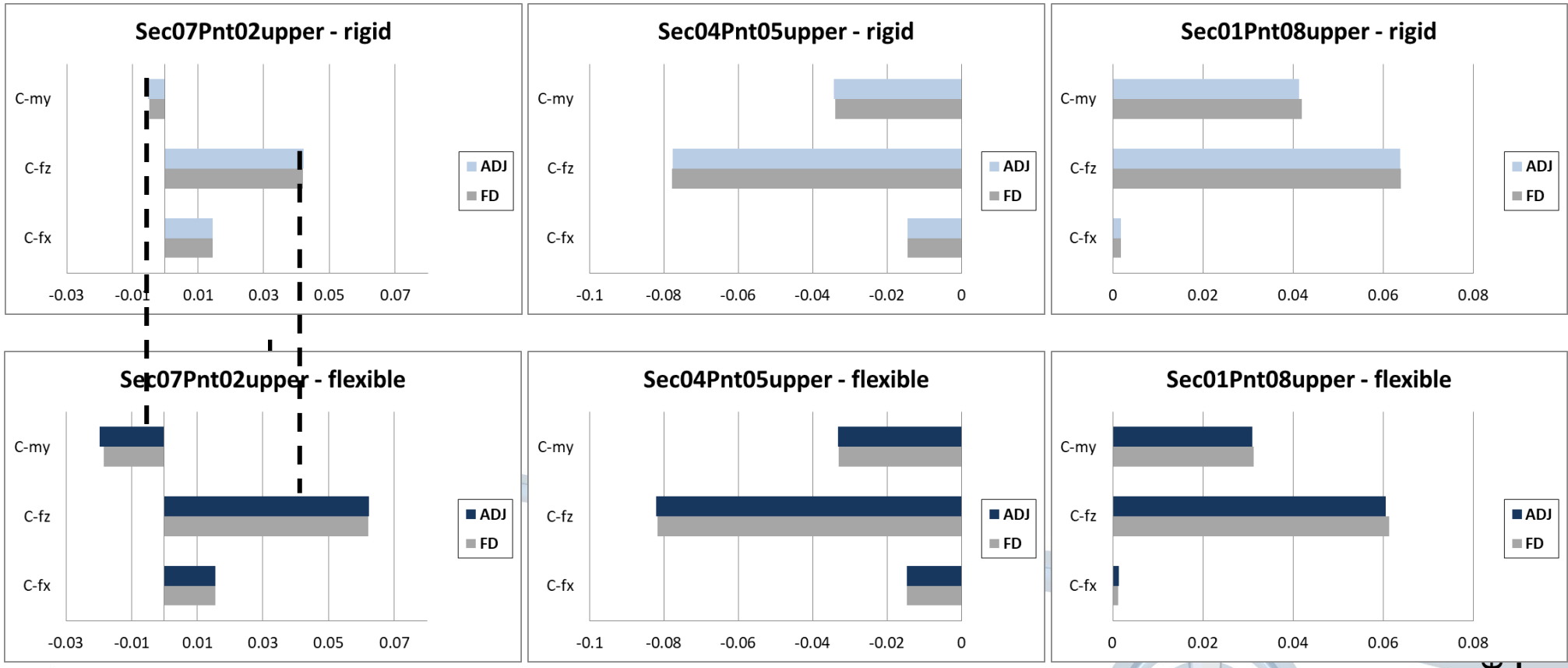


The Coupled Aeroelastic Gradient

- Validating the gradients @DLR

- The Aerodynamic Gradients

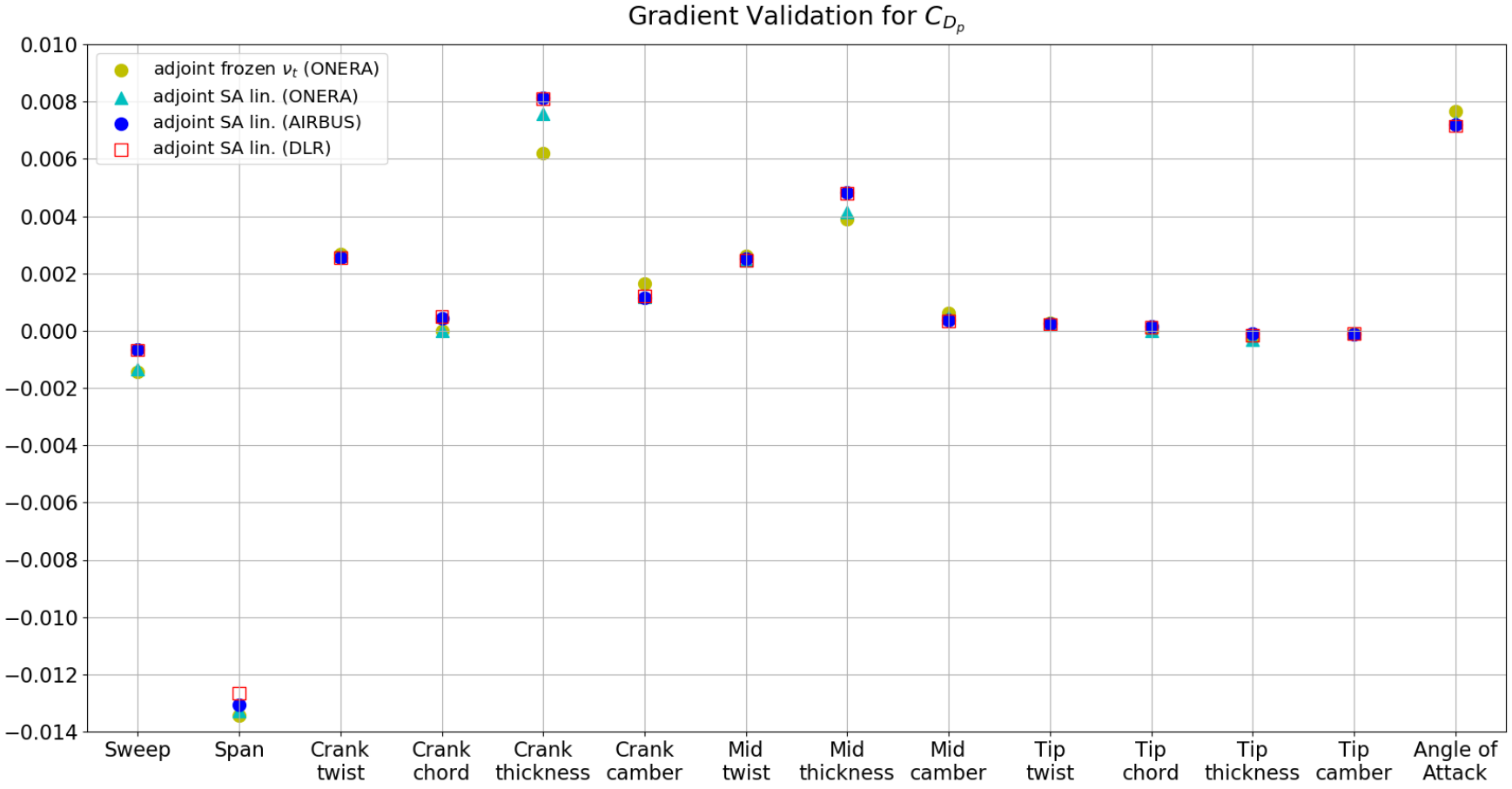
- The Aeroelastic Gradients



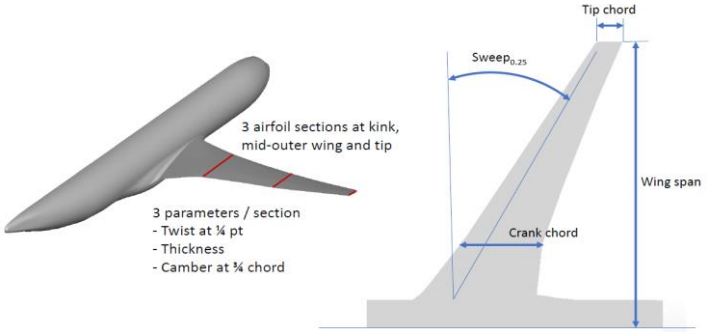
The Coupled Aeroelastic Gradient

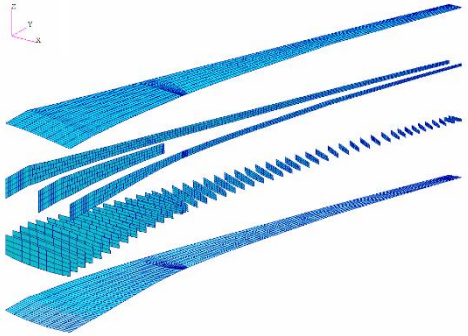
Contribution from ONERA THE FRENCH AEROSPACE LAB AIRBUS

- Validating the gradients among MADELEINE partners



Common parameterization & CSM model

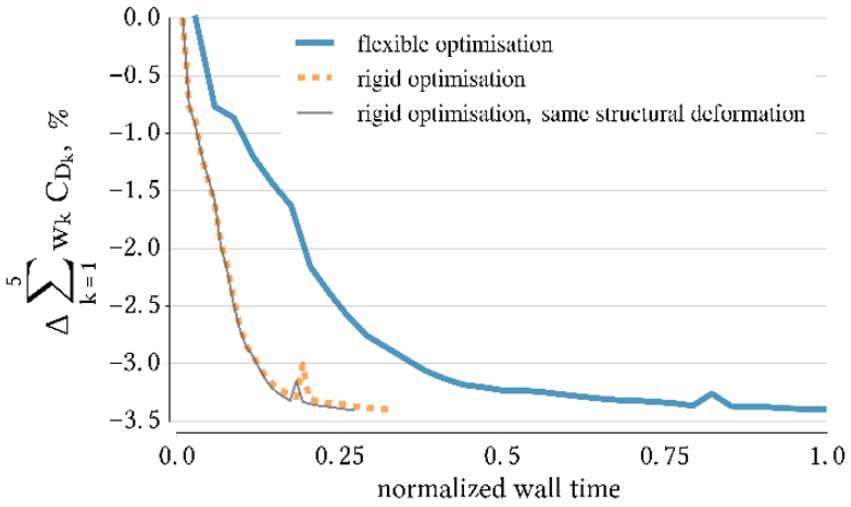


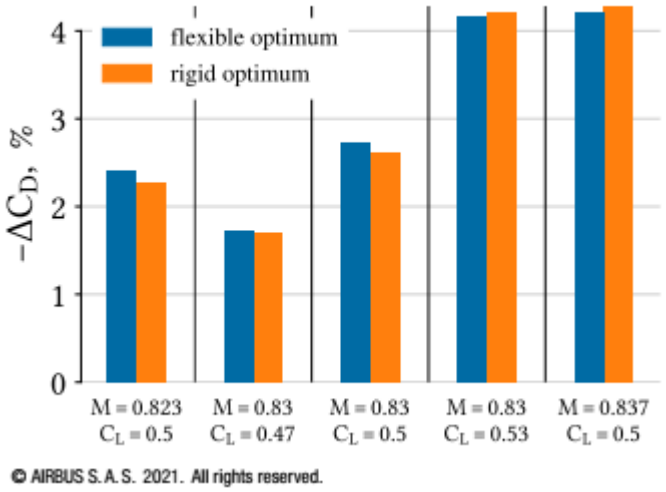


The Benefit of the Coupled Aeroelastic Gradient

Contribution from AIRBUS

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





(*)

flexible rigid

** 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

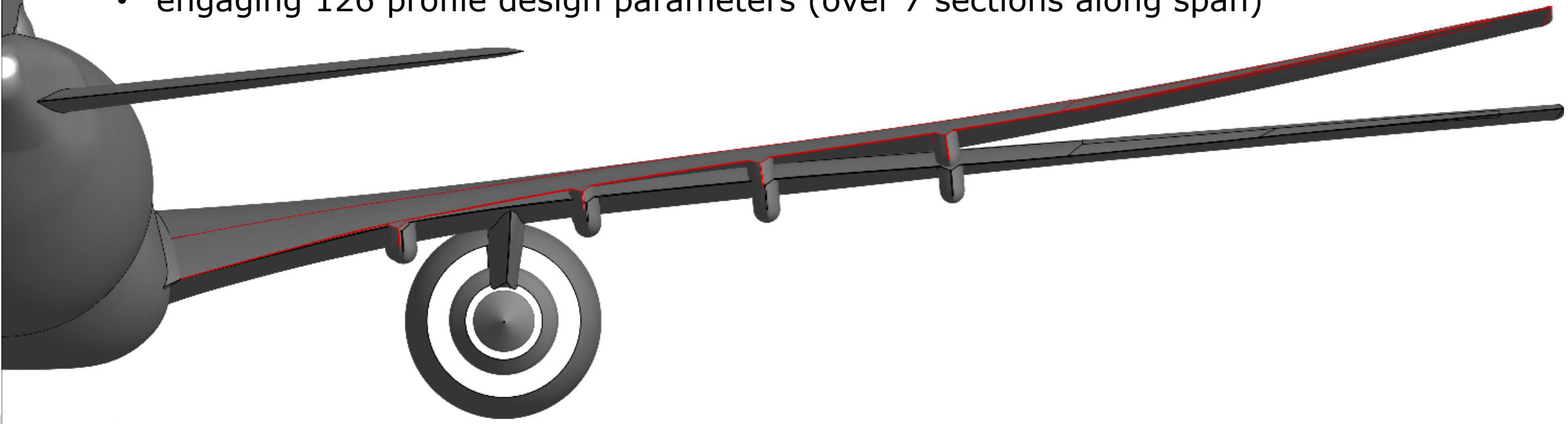
- Starting from which wing structure stiffness does the use of coupled aeroelastic adjoint pay off?

Idea of investigation:

- Generate several CSM models by reducing the Young's modulus (E) and the shear modulus (G) of elasticity simultaneously <u>until the linear theory limits</u> are reached
- Use the resulting CSM models in the following optimizations:
  1. compute the flight shape (CFD-CSM) for each suggested new shape and <u>run the aerodynamic adjoint</u> to compute the gradients and forward them to the optimizer (SQP)
  2. compute the flight shape (CFD-CSM) for each suggested new shape and <u>run the coupled aeroelastic adjoint</u> 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)

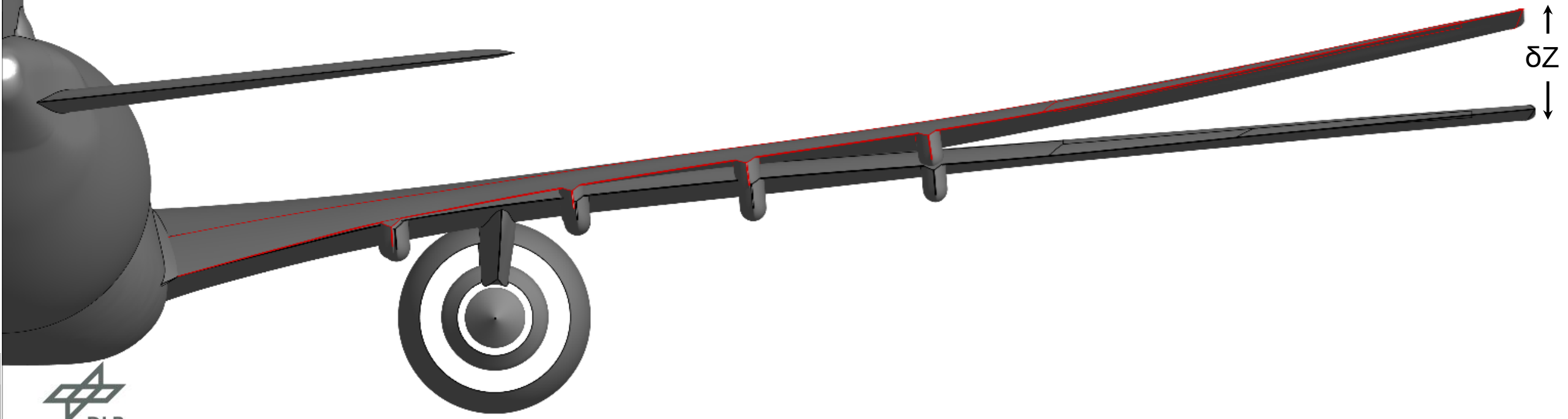


*XRF-1 Reference: D. Gueno, F.Gallard, J.Brezillon, Y. Merillac: Aerodynamic optimisation of a parametrised engine pylon on a mission path using the adjoint method

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

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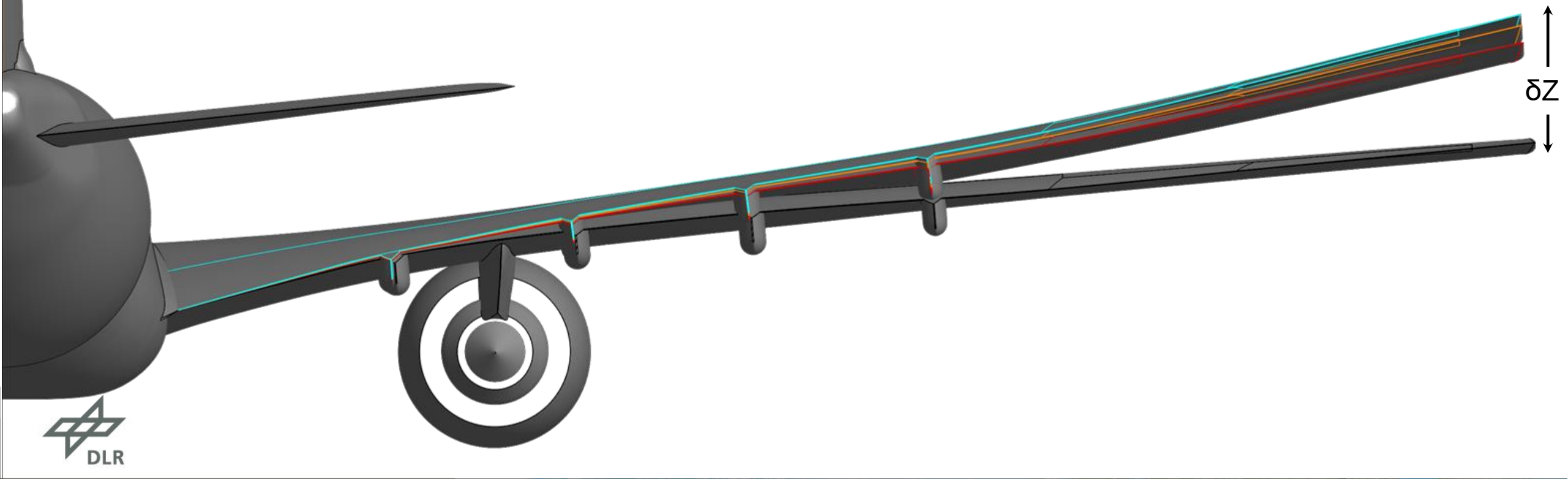
E & G 80% δZ/b = 7.65%

Investigating the Effects of Wing Flexibility on use of coupled Adjoint

- The CSM models

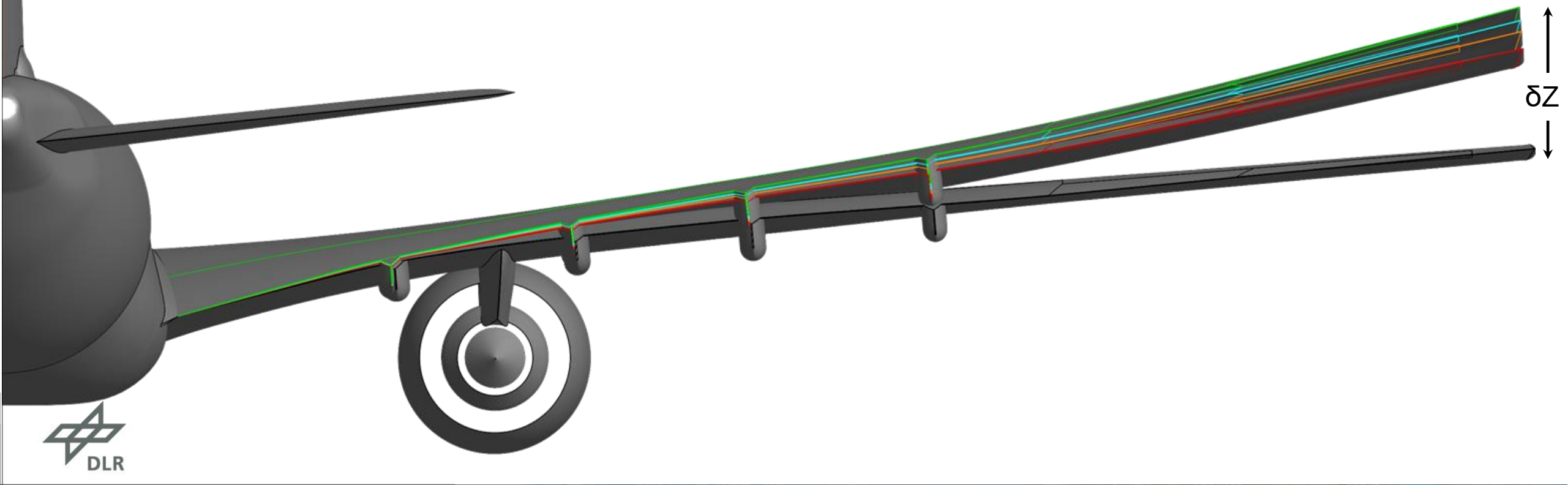
E & G 100% (of values of baseline CSM model) δZ/b = 6.50%
E & G 80% δZ/b = 7.65%
E & G 70% δZ/b = 8.34%



Investigating the Effects of Wing Flexibility on use of coupled Adjoint

- The CSM models

E & G 100% (of values of baseline CSM model)	δZ/b = 6.50%
E & G 80%	δZ/b = 7.65%
E & G 70%	δZ/b = 8.34%
E & G 60%	δZ/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)	δZ/b = 6.50%
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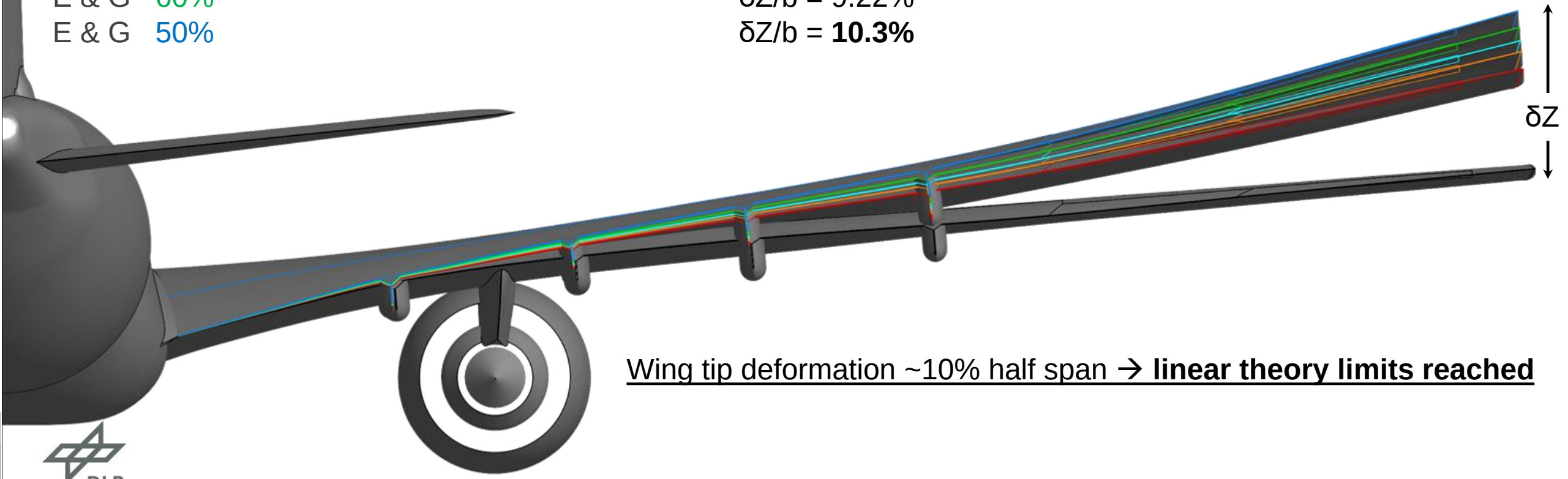
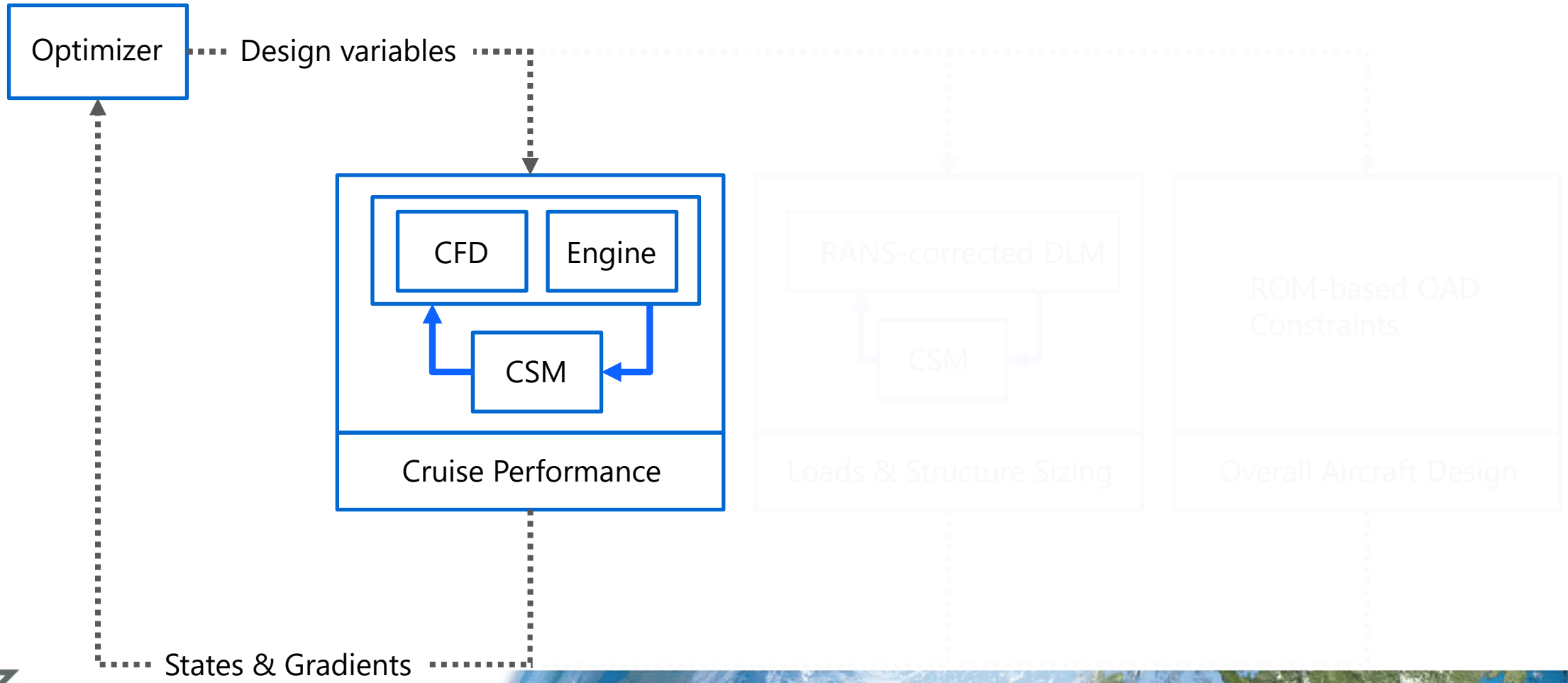
E & G 60%	δZ/b = 9.22%
E & G 50%	δZ/b = **10.3%**



Wing tip deformation ~10% half span → **linear theory limits reached**

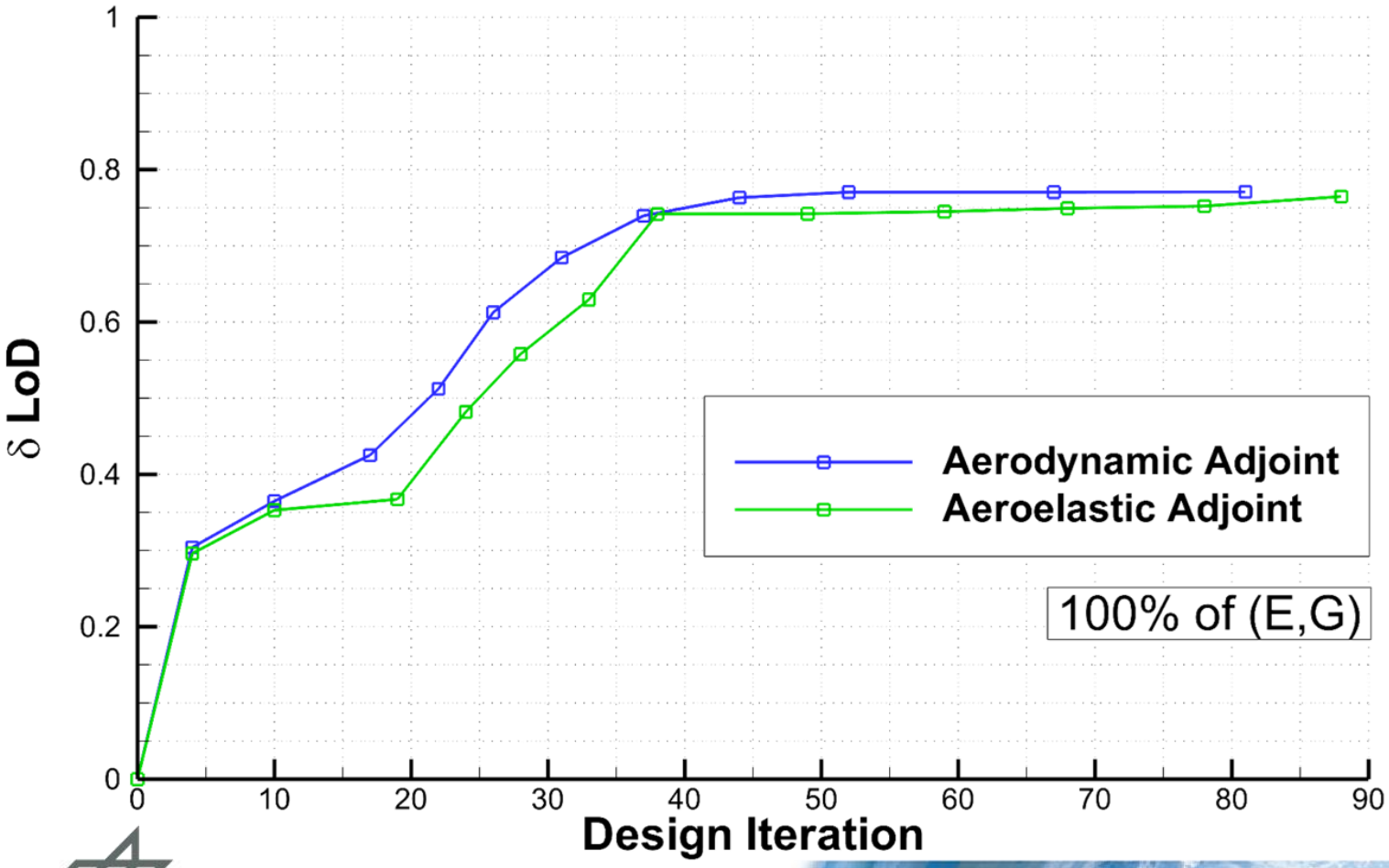
Investigating the Effects of Wing Flexibility on use of coupled Adjoint

Optimization Chain



Investigating the Effects of Wing Flexibility on use of coupled Adjoint

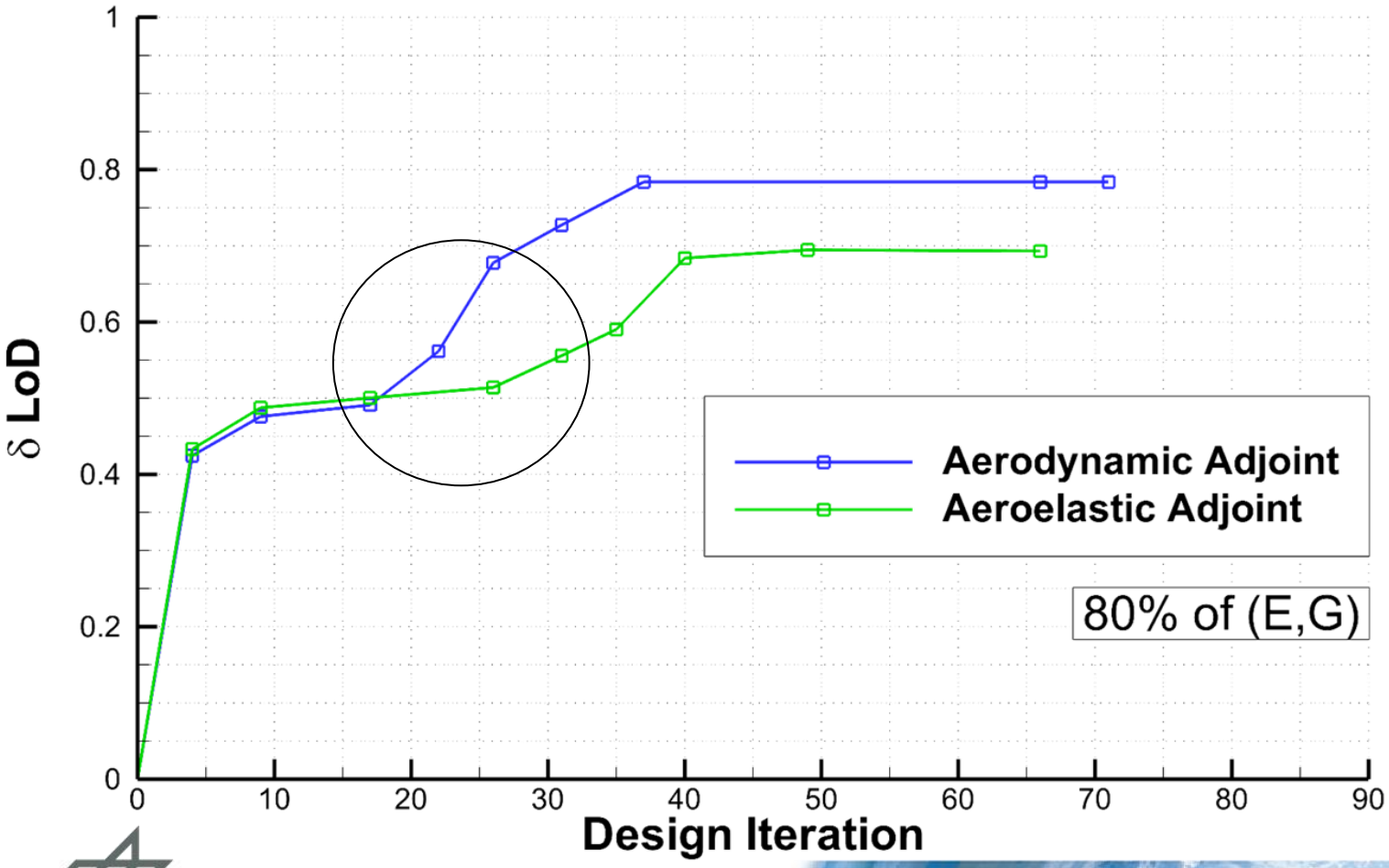
Optimization Results: 100% of E&G, δZ/b = 6.50%



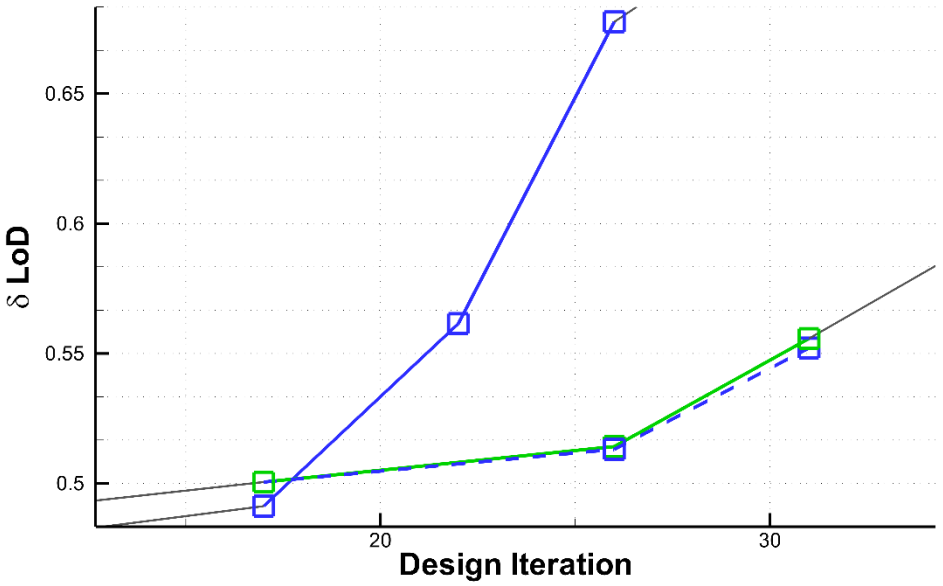
Both optimizations reach similar value of the objective

Investigating the Effects of Wing Flexibility on use of coupled Adjoint

Optimization Results **80% of E&G, δZ/b = 7.65%**

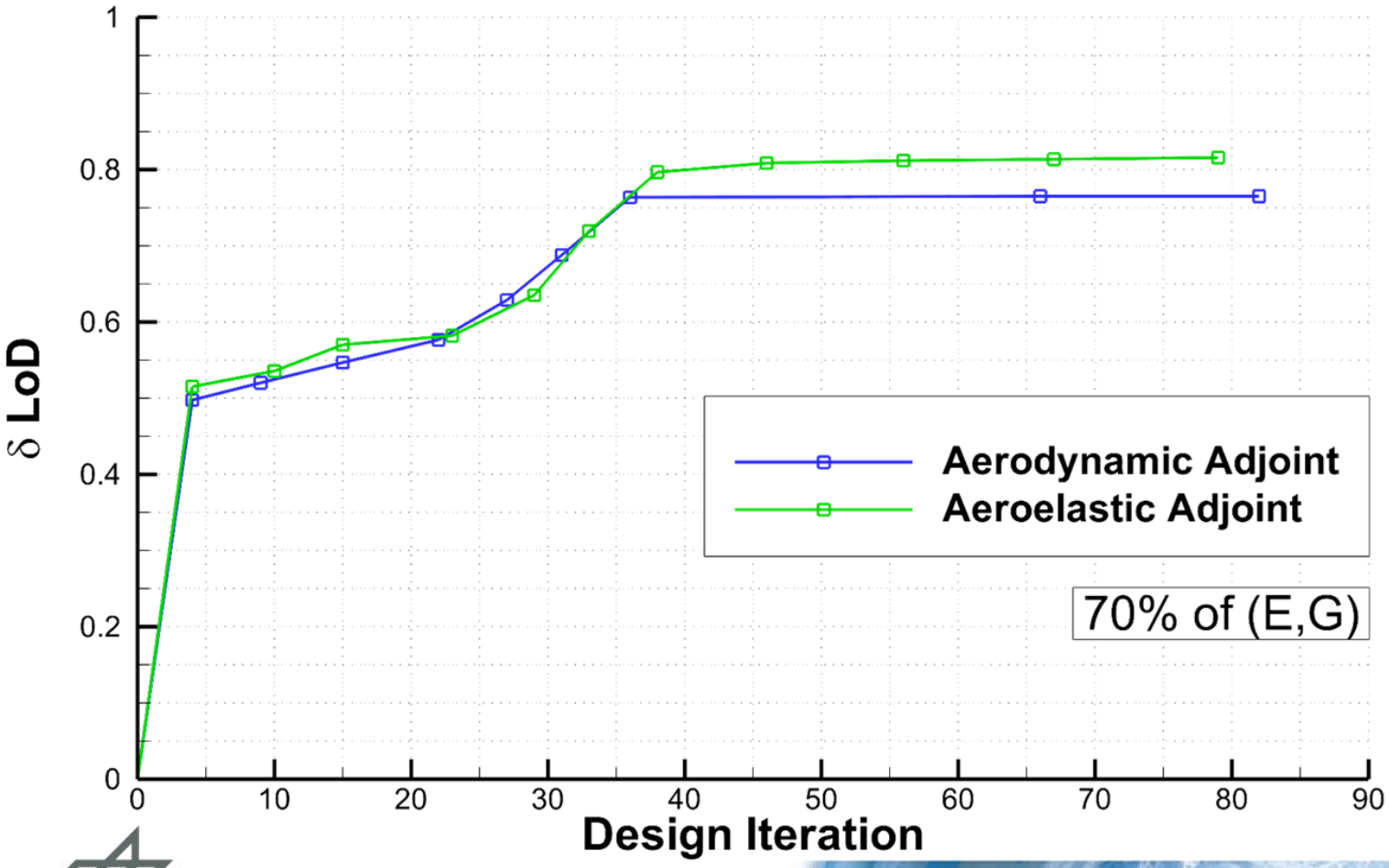


- Restart the aeroelastic adjoint based optimization while employing the aerodynamic adjoint



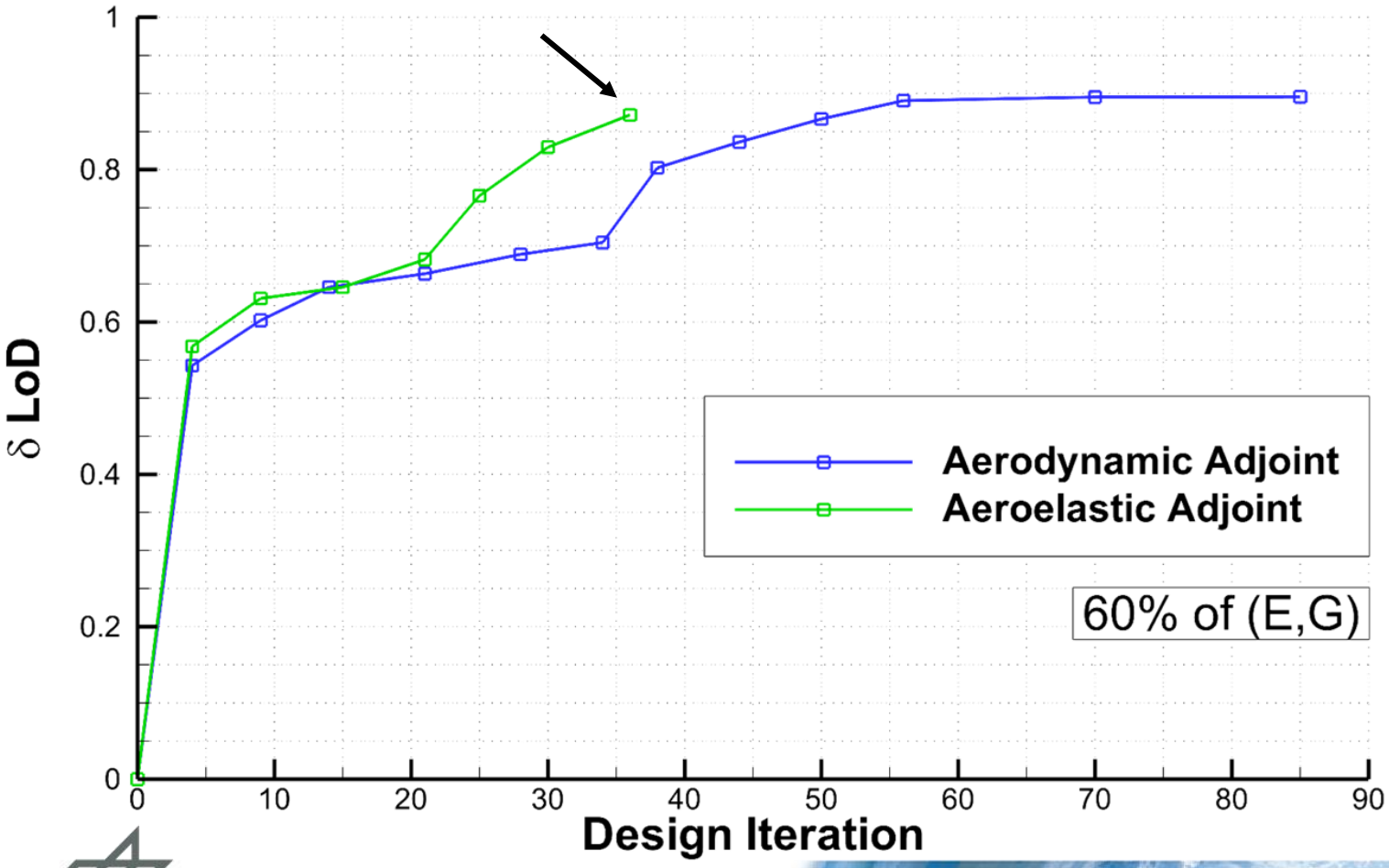
Investigating the Effects of Wing Flexibility on use of coupled Adjoint

Optimization Results 70% of E&G, δZ/b = 8.34%



Investigating the Effects of Wing Flexibility on use of coupled Adjoint

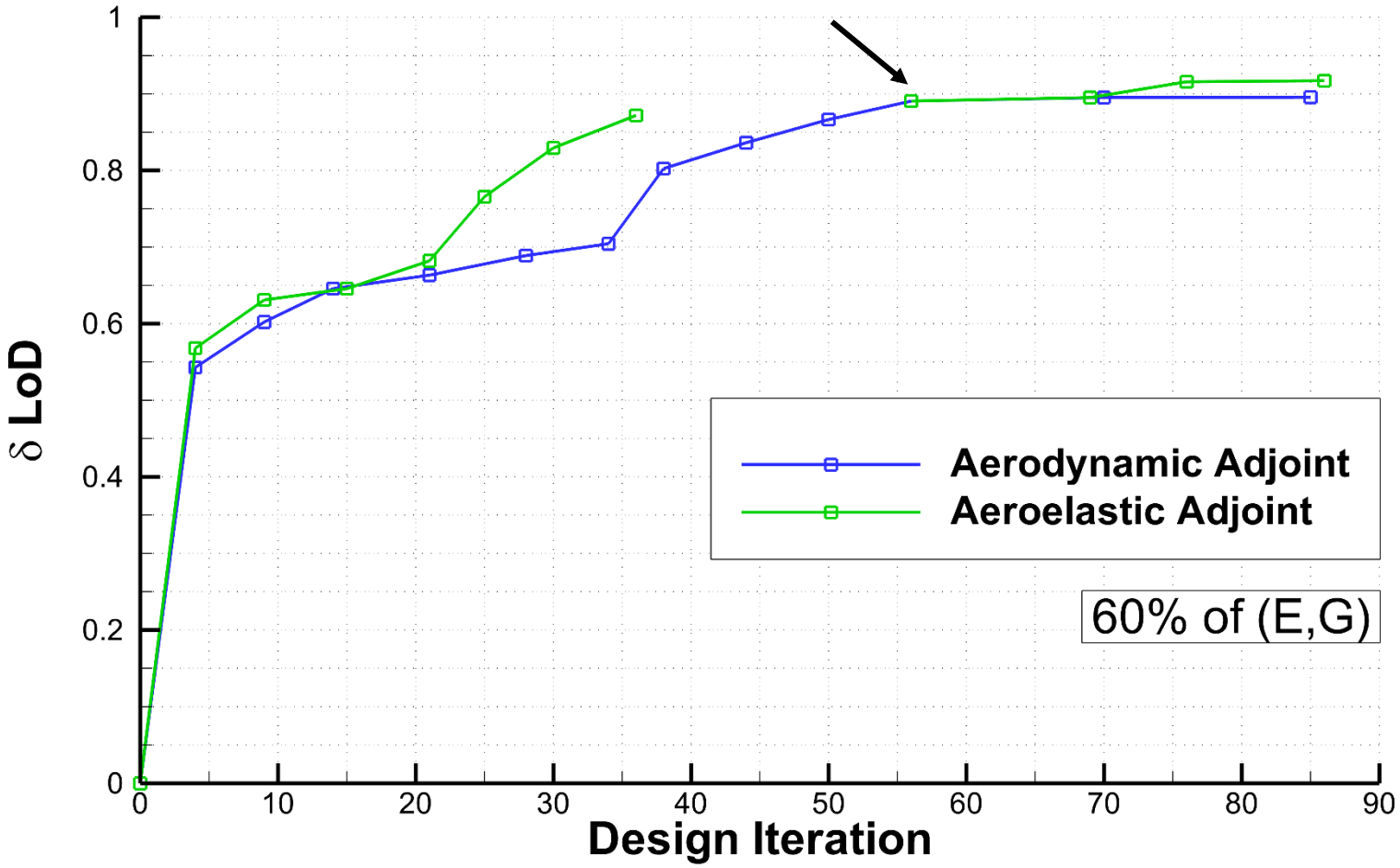
Optimization Results 60% of E&G, δZ/b = 9.22%



- 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, δZ/b = 9.22%

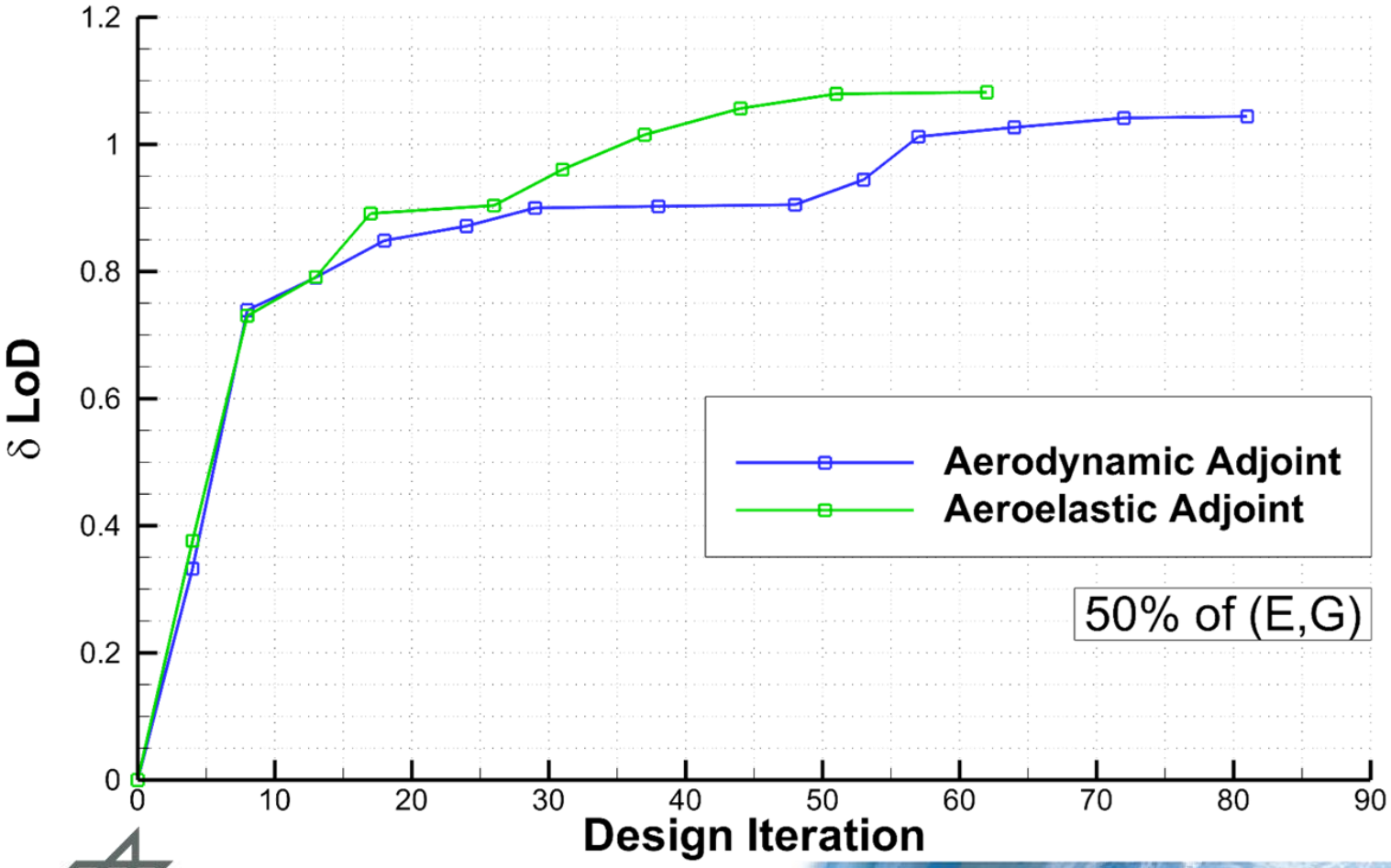


- Restart the aeroelastic adjoint based optimization while employing the aerodynamic adjoint
  - **No improvement obtained**

- 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, δZ/b = 10.3%



Conclusions

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

- First trends showed that the benefit of the coupled adjoint appears starting from values of δZ/b ~8%
  - To be able to conclude, these investigations should be done for differnt configurations and with different optimization algorithms

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

The authors would like to thanks AIRBUS and ONERA for their contributions to this talk

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