Status of Gradient-based Airframe MDO at DLR “The VicToria Project”

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1st European MDO Workshop (24.10.2017)

German Aerospace Center (DLR)

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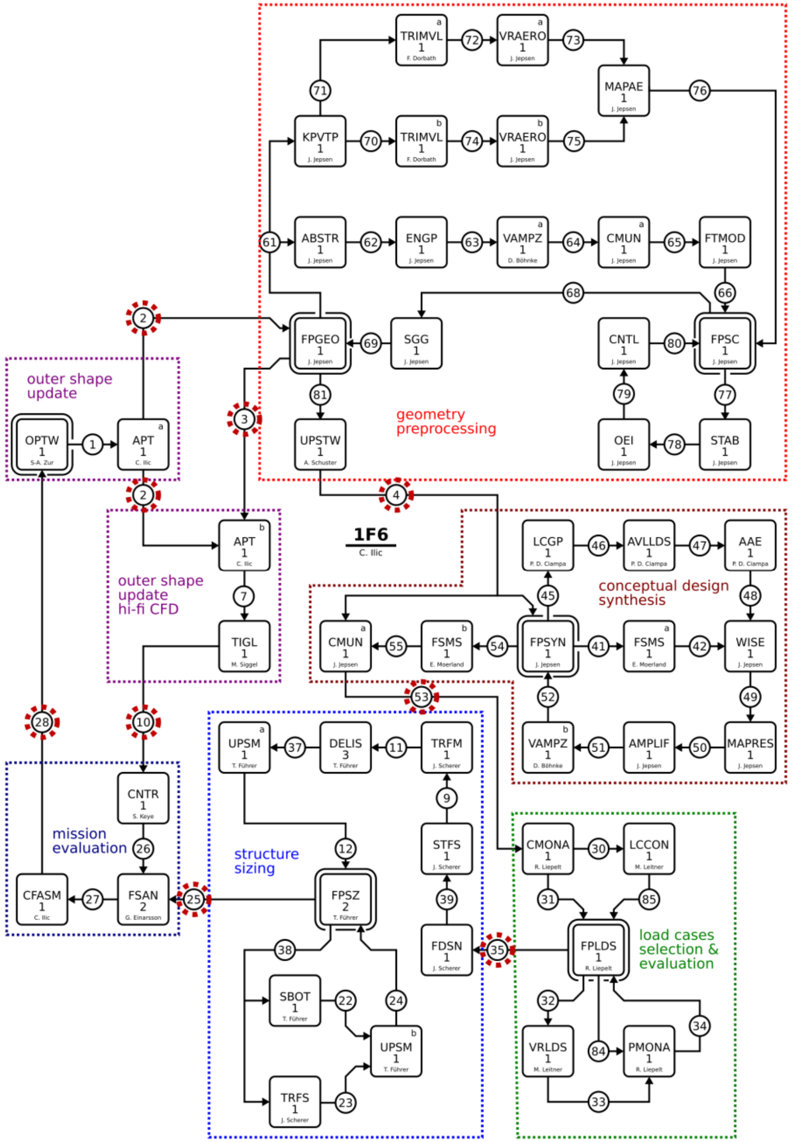
Background

- The complexity and the computational cost of the problem in MDO are significantly higher than that of single disciplinary optimizations
  - → Optimization algorithms that drive high-fidelity MDO need to be efficient
  - → motivates the use of <u>gradient-based algorithms</u>

(provided that the computation of the required gradients itself is efficient)

- *if number of obj&const is low → Adjoint*
- *if number of des. vars. is low → Finite Differences*

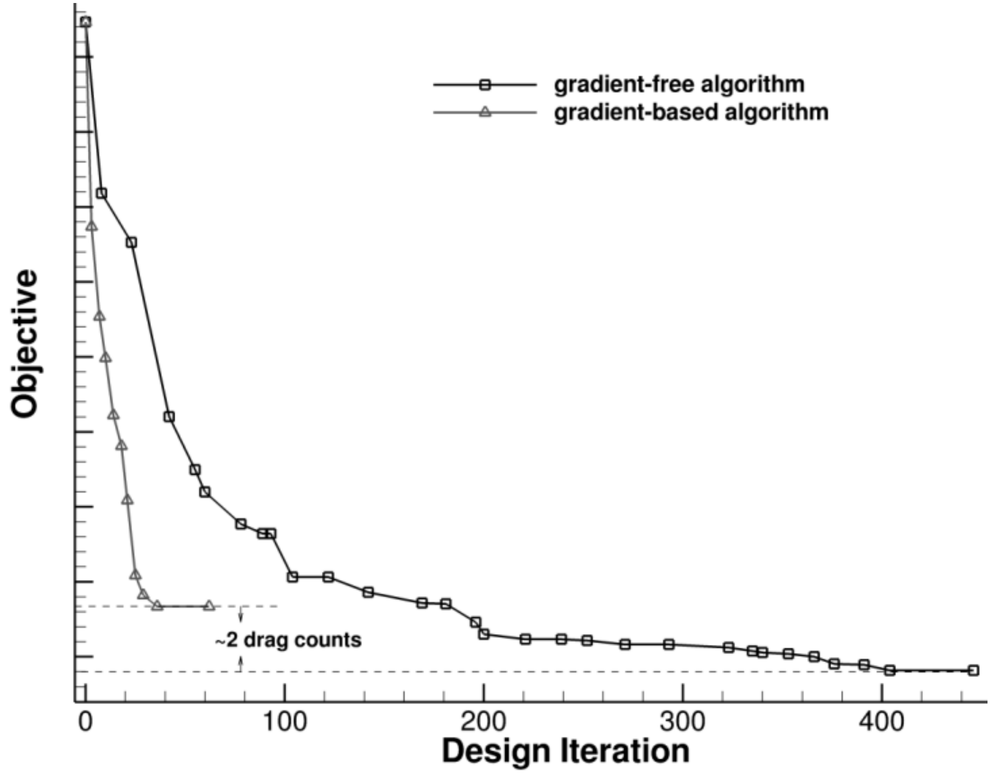


Background

- Since gradient-based algorithms can efficiently find the nearest *local* optimum, we consider them more suitable for the final design stages; fine-tuning. (However, this is not a common view.)

- For detailed design
  - Wing profiles
  - Structural material thicknesses
  - planform parameters ?

  (how does the industry see this?)



Gradient-Based MDO Chain in VicToria

Overall Aircraft Design

Modify wing&tail planform design parameters
Improve Objective
Maintain geometrical, stability and performance constraints

Gradient-based with multi-start Or nearly global gradient-free algorithm

planform

Gradient-Based Aero-Engine-Structure Optimization

Modify wing-pylon-nacelle-belly fairing outer shape
Modify engine position and scale the engine
Modify structural thicknesses

Improve Objective

Maintain geometrical, aerodynamic, engine and structural constraints

High-fidelity based tools

Contents

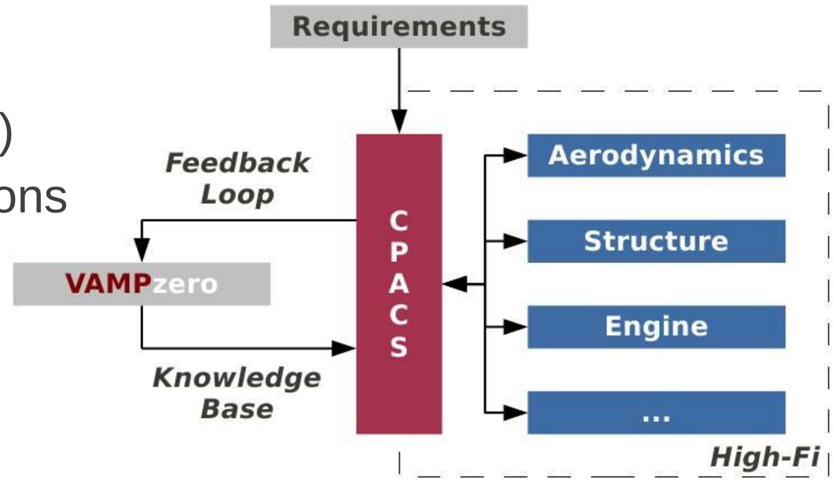
Overall Aircraft Design

Main features

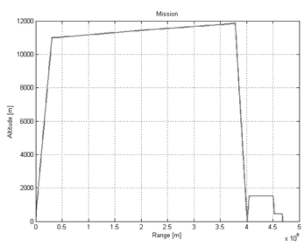
- Based on **Conceptual** design methods
- Object oriented structure (multi-fi support)
- **Knowledge base** for multiple configurations
- **CPACS** exporting capabilities for hi-fi

Process

- **Input:** TLAR & constraints provided
- **Output:** sized aircraft, performance

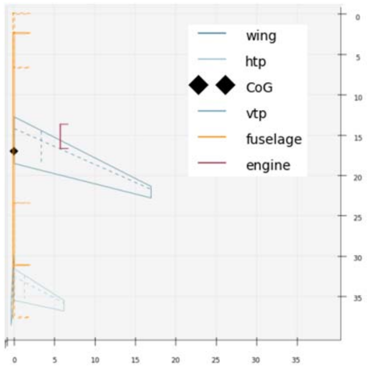


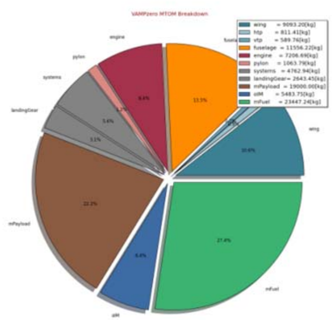
Aircraft TLAR



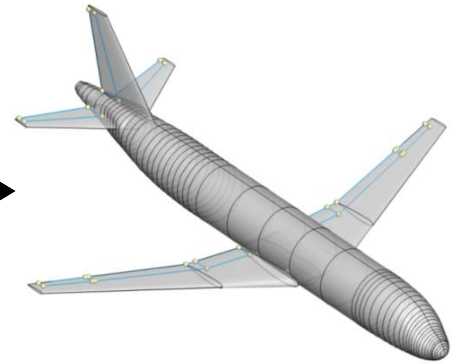
Mission, PAX, Mach, etc.

Conceptual synthesis Output





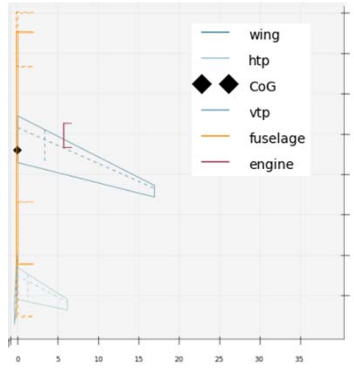
Extended CPACS export

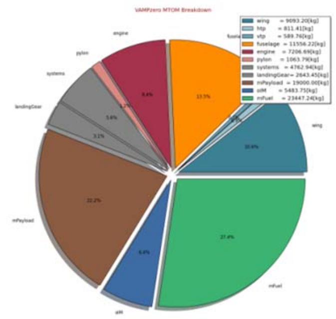


Overall Aircraft Design

Gradients Process

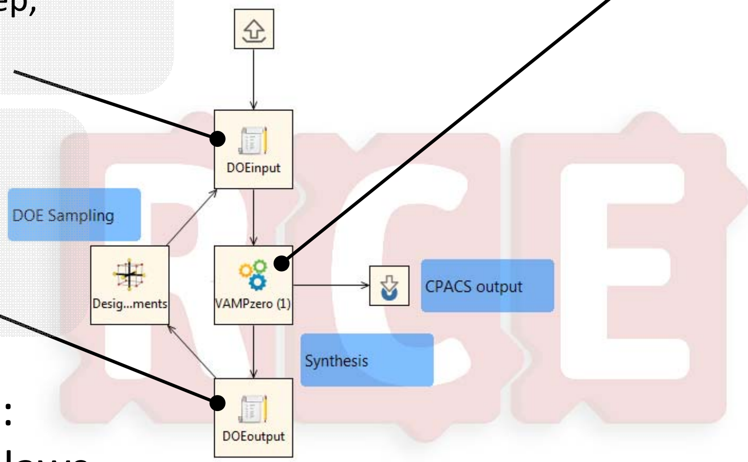
- Finite difference approach
- A DOE on TLAR and Aircraft Parameters
- For each variation → a fully converged aircraft





Independent Parameters:
Mission: Design Range, Mach@Cruise
Aircraft: Aspect Ratio, Wing sweep, Wing Area, Wing taper ratio

State Parameters:
CD0 , CL@Cruise , CD @ Cruise
Mission Fuel , Wing Mass, OEM
T/W, W/S



Conceptual synthesis Output

Challenges for Gradients:

- presence of heuristic laws
- presence of multiple convergence loops

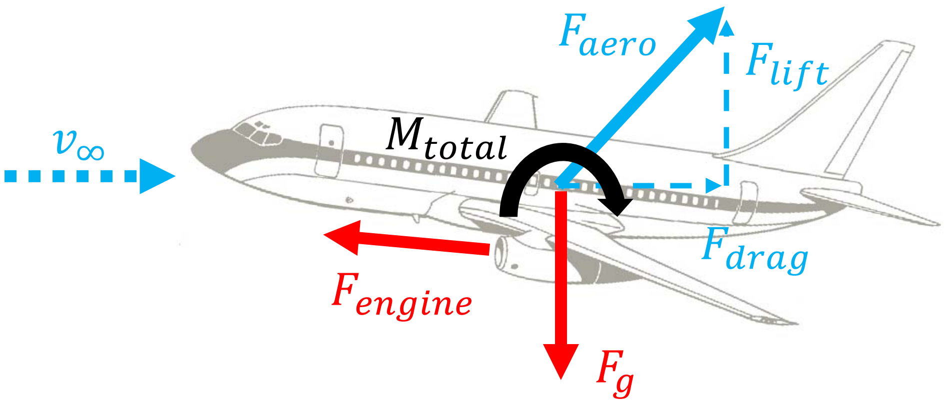
Contents

Disciplinary Gradient Capabilities

Aerodynamic Optimization with Powered Engines

- In aerodynamic optimization, two of the points of interest are:
  - Engine integration effects
  - Trim constraints for steady-state flight

- To be able to tackle these points of interest
  - Adjoint consistent engine boundary treatment implemented



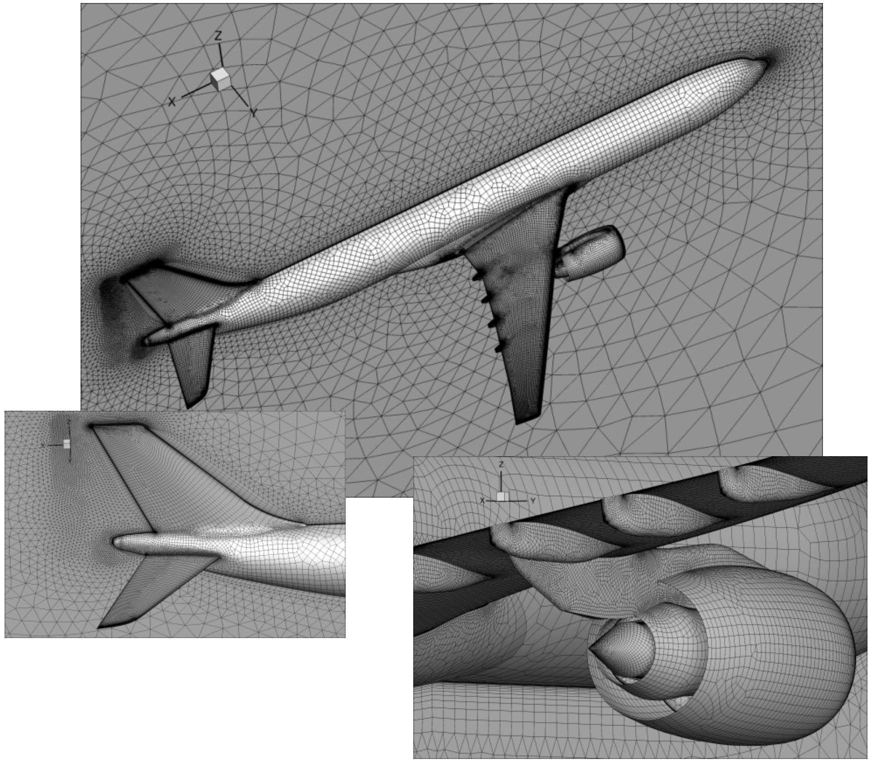
Constraints:

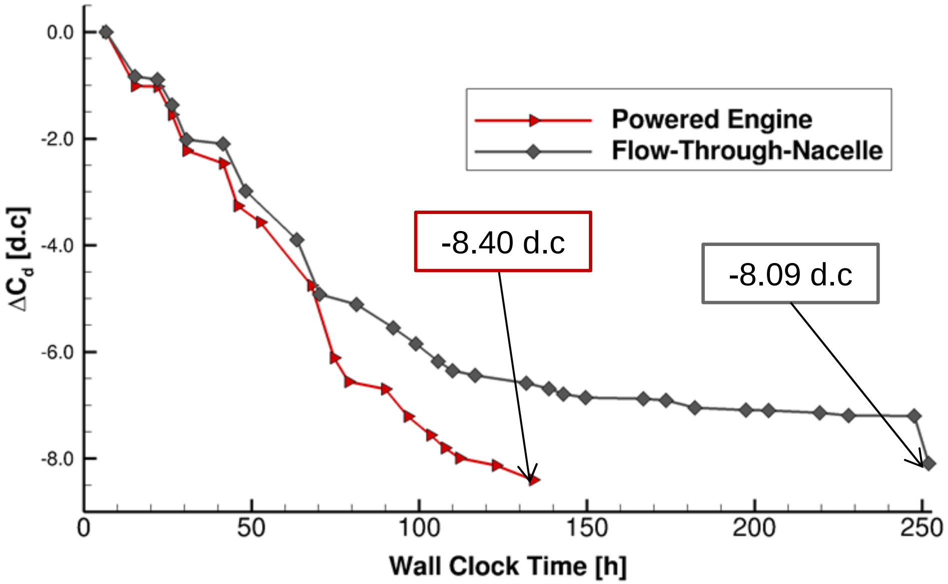
$$\left.\begin{aligned} \sum C_{Fx} &= 0 \\ \sum C_{Fz} &= 0 \\ \sum C_{My} &= 0 \end{aligned}\right\} \quad \mathbf{C} = \begin{bmatrix} C_{Fx} \\ C_{Fz} \\ C_{My} \end{bmatrix} = \mathbf{0}$$

Disciplinary Gradient Capabilities

Aerodynamic Optimization with Powered Engines

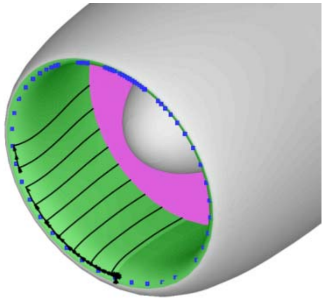
➢ Ran two optimizations to estimate the effect of optimizing with powered engine



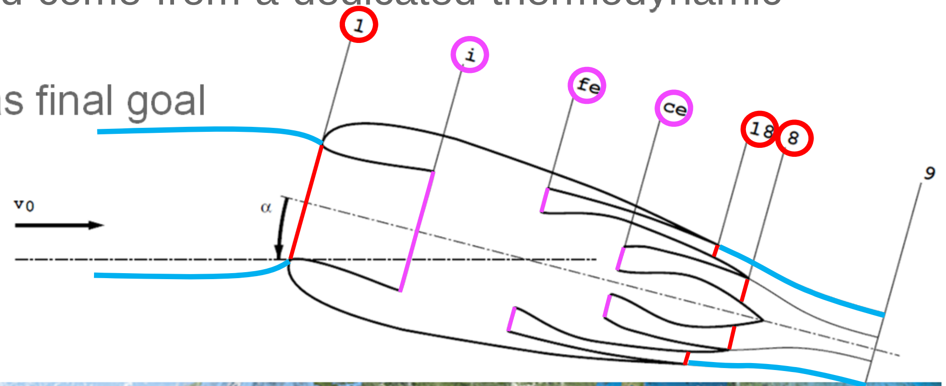


Disciplinary Gradient Capabilities

Aerodynamic Optimization with Powered Engines



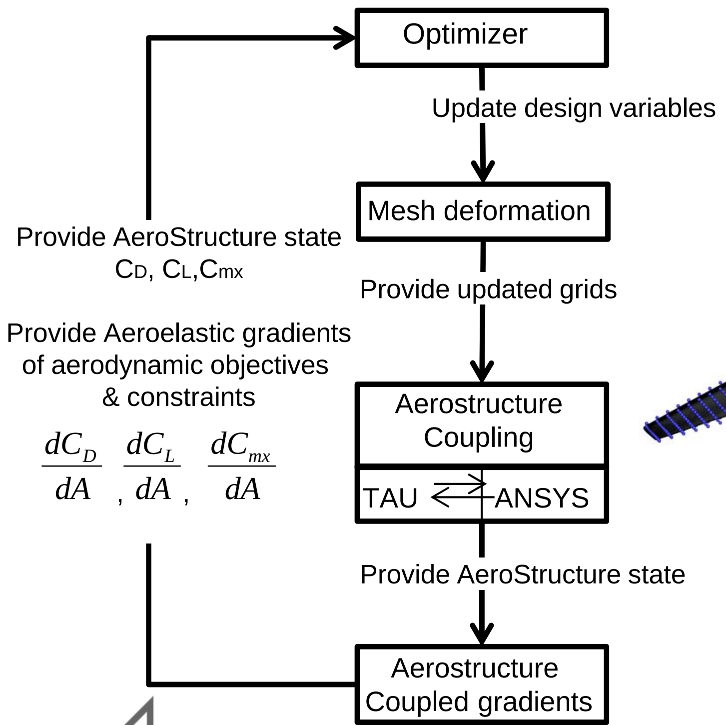
- *Issues to consider:*
  - *Thrust/Drag Book-keeping*
    - thrust/drag-bookkeeping is usually evaluated by dedicated postprocessing tools
    - these tools need to be differentiated to deliver the right-hand-side (cost functional) Jacobian for the adjoint CFD solver
    - simplified approach using fixed boundary markers to assign force contributions to thrust or drag was used instead
  - *Consistency between CFD and Thermodynamic Engine model*
    - engine BCs used in CFD model should come from a dedicated thermodynamic engine model
    - automated coupling and consistency as final goal

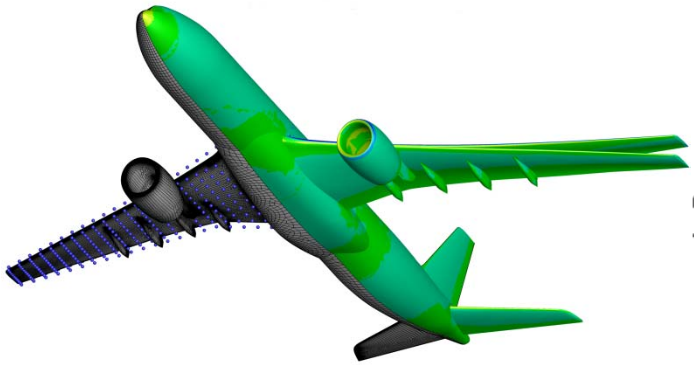


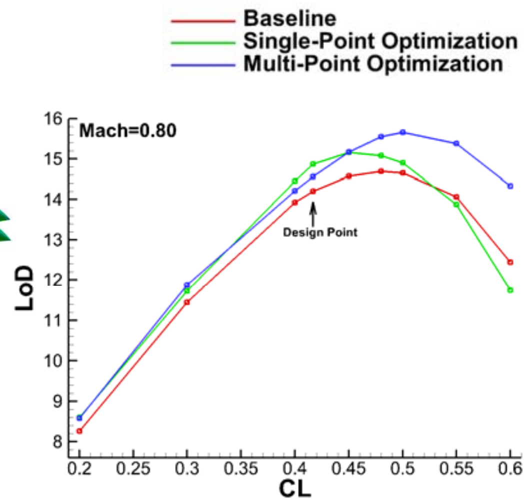
Disciplinary Gradient Capabilities

Aeroelastic Coupled Adjoint

- The approach is implemented in TAU and can couple to several commercial structure solvers
- Gradients were validated for several test cases







Contents

- Background
- Overall Aircraft Design
- Aero-Engine-Structure Design
  - Disciplinary Gradient Capabilities
  - Aero-Structure Optimization Problem (core of this talk)
- Conclusions

Aero-Structure Optimization Problem

➢ The aerostructural optimization problem contains two parts.

1. Improve the aerodynamic performance for the wing's current flight shape.
2. Reduce the mass of the structure while guaranteeing that the structure holds under the critical/sizing loads

For both parts of the problem, the gradients of all objectives and constraints with respect to all design parameters are required throughout the optimization

Aero-Structure Optimization Problem

- The aerostructural optimization problem contains two parts.

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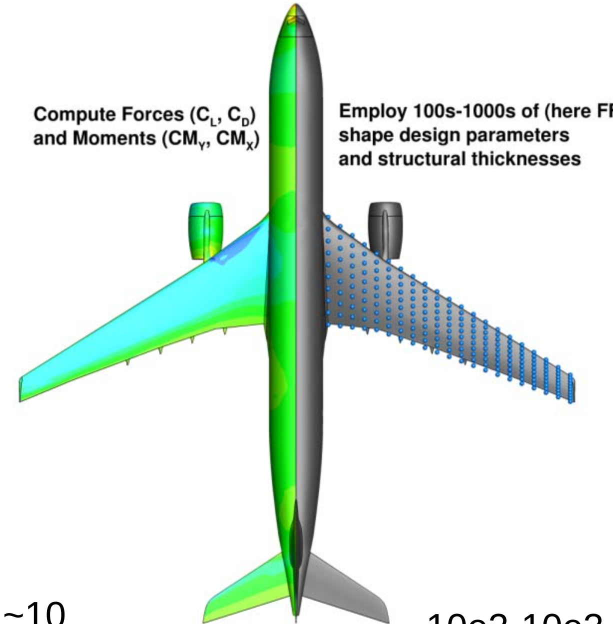
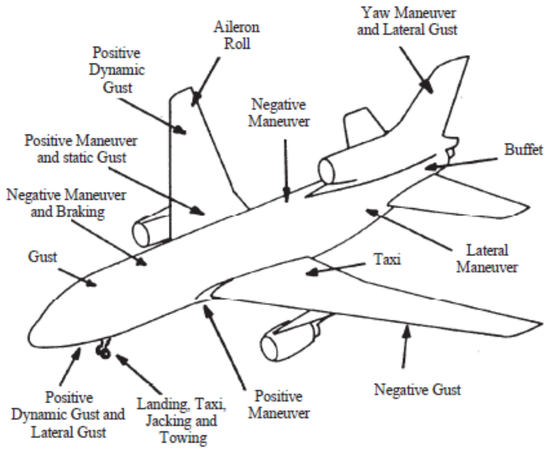


~10
objectives and constraints

~10e2-10e3
design variables

2. Reduce the mass of the structure while guaranteeing that the structure holds under the critical/sizing loads



RWTH Aachen, Institut für Luft- und Raumfahrtsysteme (ILR), Flugzeugbau II – Belastungsmechanik 2004

Wing sizing loads	
front gust	6%
vertical gust	30%
landing shock	14%
taxi	6%
maneuver	36%
others	8%

Luftfahrttechnisches Handbuch (LTH)

10e5 load cases
sizing ~100s load cases
~10e2-10e3 constraints

Adjoint approach is suitable here

Aero-Structure Optimization Problem

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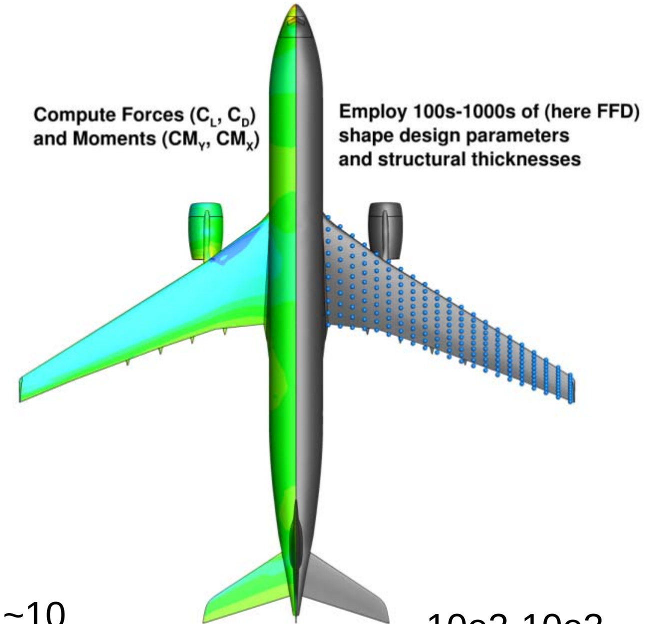

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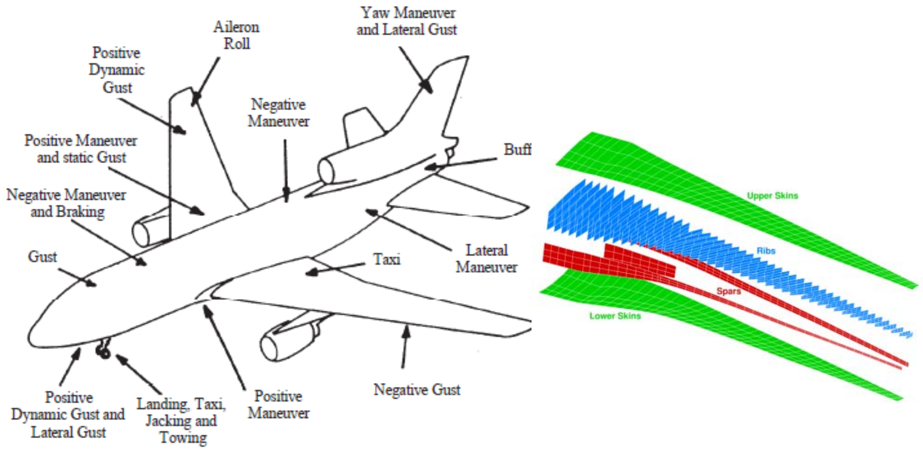

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10e5 load cases
sizing ~100s load cases
~10e2-10e3 constraints

~10e2-10e3 design variables

Adjoint approach is <u>not</u> suitable here

Aero-Structure Optimization Problem

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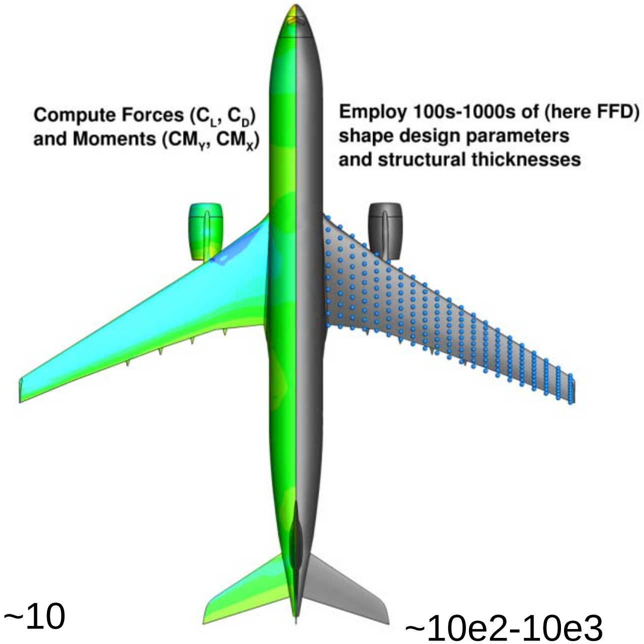

~10 objectives and constraints

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Adjoint approach is suitable here

2. Reduce the mass of the structure while guaranteeing that the structure holds under the critical/sizing loads

For adjoint to be suitable here the constraints need to be aggregated (thousands to tens), however

- Conservative → not a fine tuning approach
- Not always possible/practical to differentiate (commercial) software

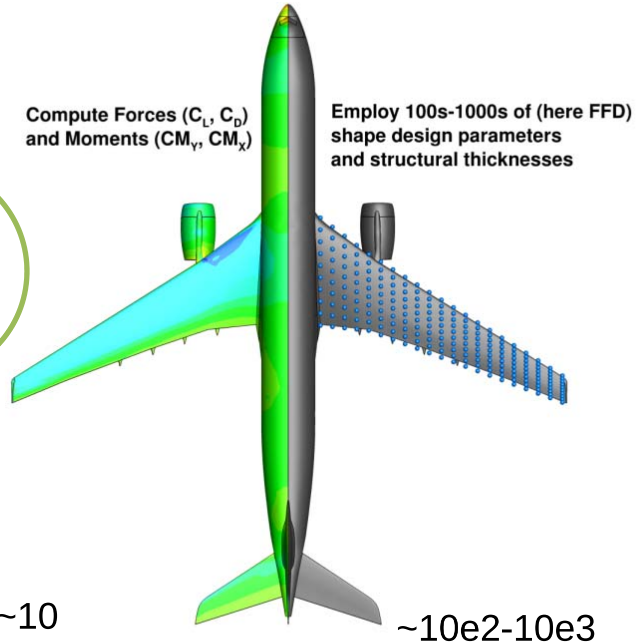
There is no guarantee the sizing load cases will be the sizing ones as the optimization progresses → how to take a set of sizing load cases? → number of constraints can change during opt

It is claimed that MDO can help in unconventional configurations, we barely know how to engage loads for conventional configurations in MDO

Aero-Structure Optimization Problem

➢ The aerostructural optimization problem contains <u>two parts</u>.

1. Improve the aerodynamic performance for the wing's current flight shape.



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Aero-Structure Optimization Problem

➢ The aerostructural optimization problem contains <u>two parts</u>.

2. Reduce the mass of the structure while guaranteeing that the structure holds under the critical/sizing loads

Target is to check which approach (in computing gradients) is more efficient and brings more improvement

1. get a realistic aircraft model, <u>with loads process that engages more than several predefined load cases, in order to be able to make useful conclusions</u>
2. Compute the full set of gradients (for all constraints) and check the magnitude of gradients
3. Perform aerostructural optimizations with different levels of gradients accuracies, to conclude which gradients drive the optimization.

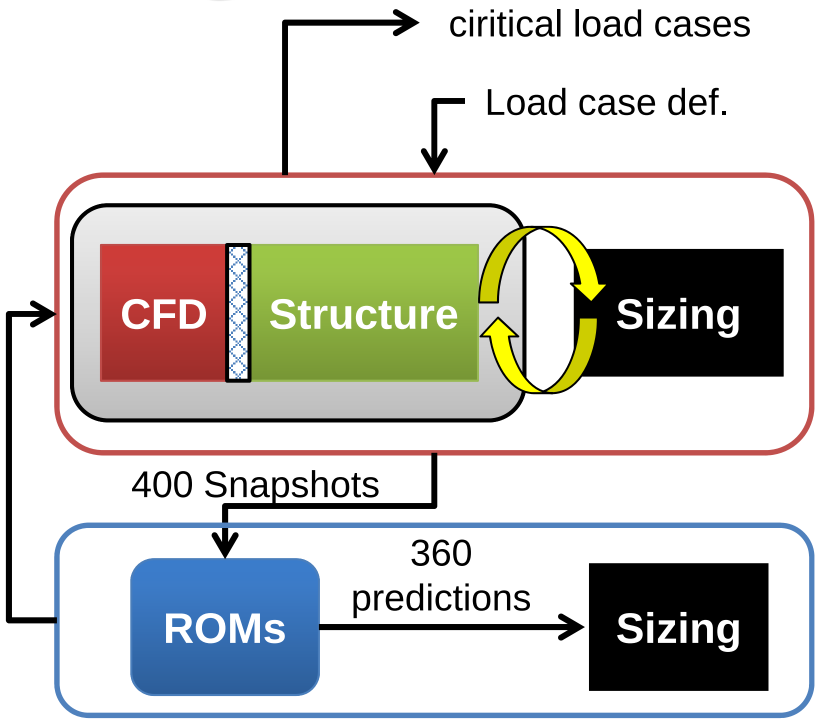
Wing sizing loads	
front gust	6%
vertical gust	30%
landing shock	14%
taxi	6%
maneuver	36%
others	8%

Aero-Structure Optimization Problem

➢ Test case definition:

- A generic transport aircraft (XRF1)
- Identify the critical/sizing aerodynamic maneuver load cases

Fuel mass [ton]	Payload [ton]	CG
0	0	34%
48	0	20%
48	69	28%
28	89	38%
0	89	32%



Aero-Structure Optimization Problem

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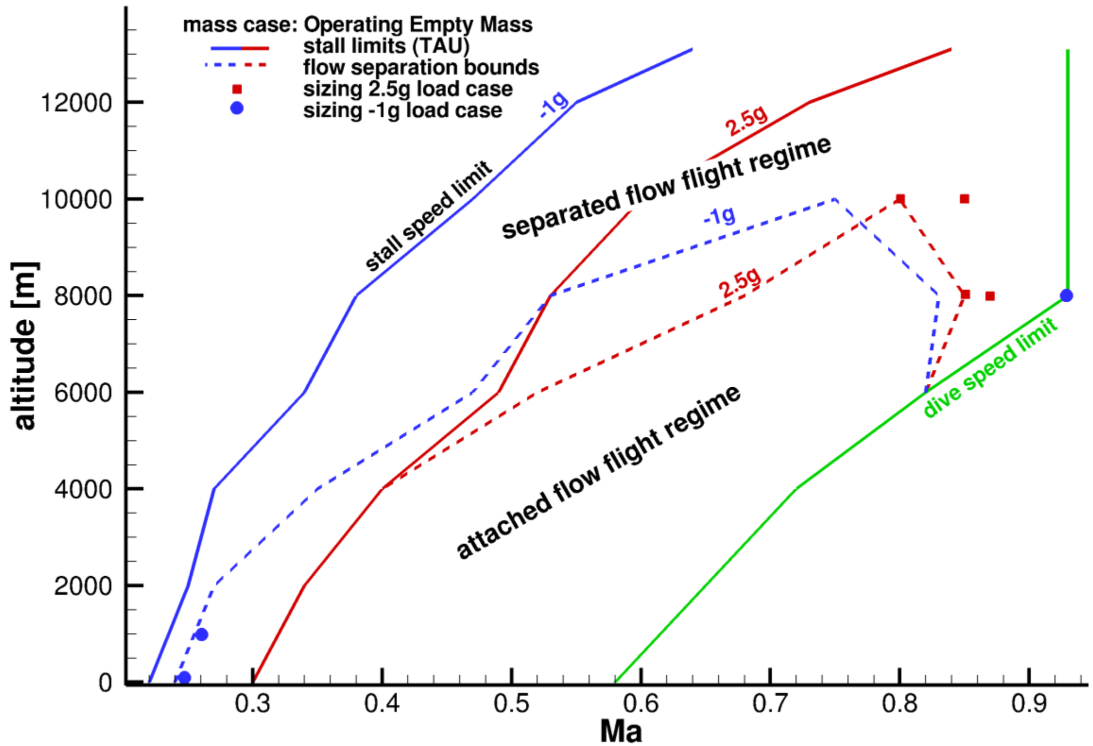
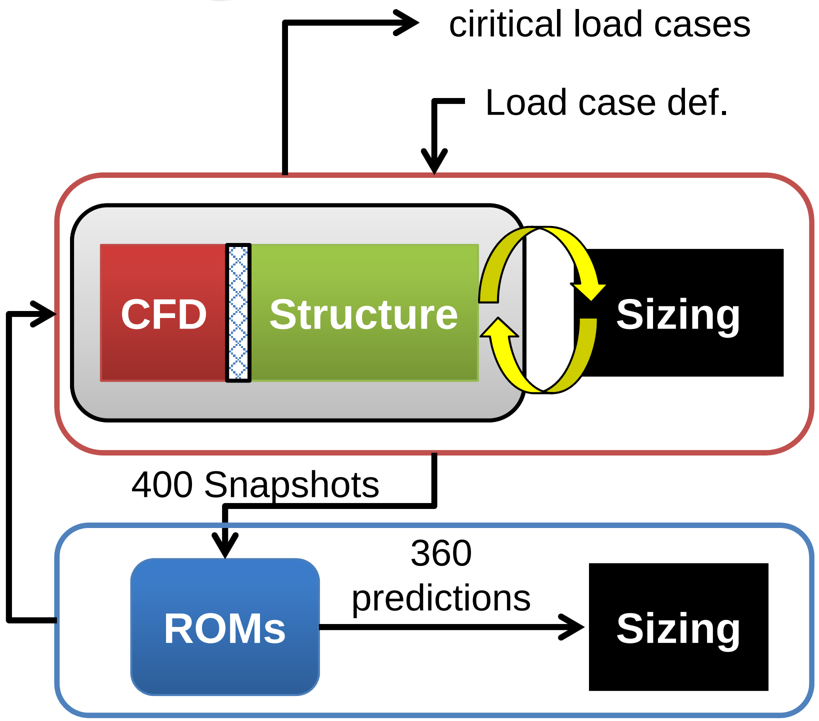




Aero-Structure Optimization Problem

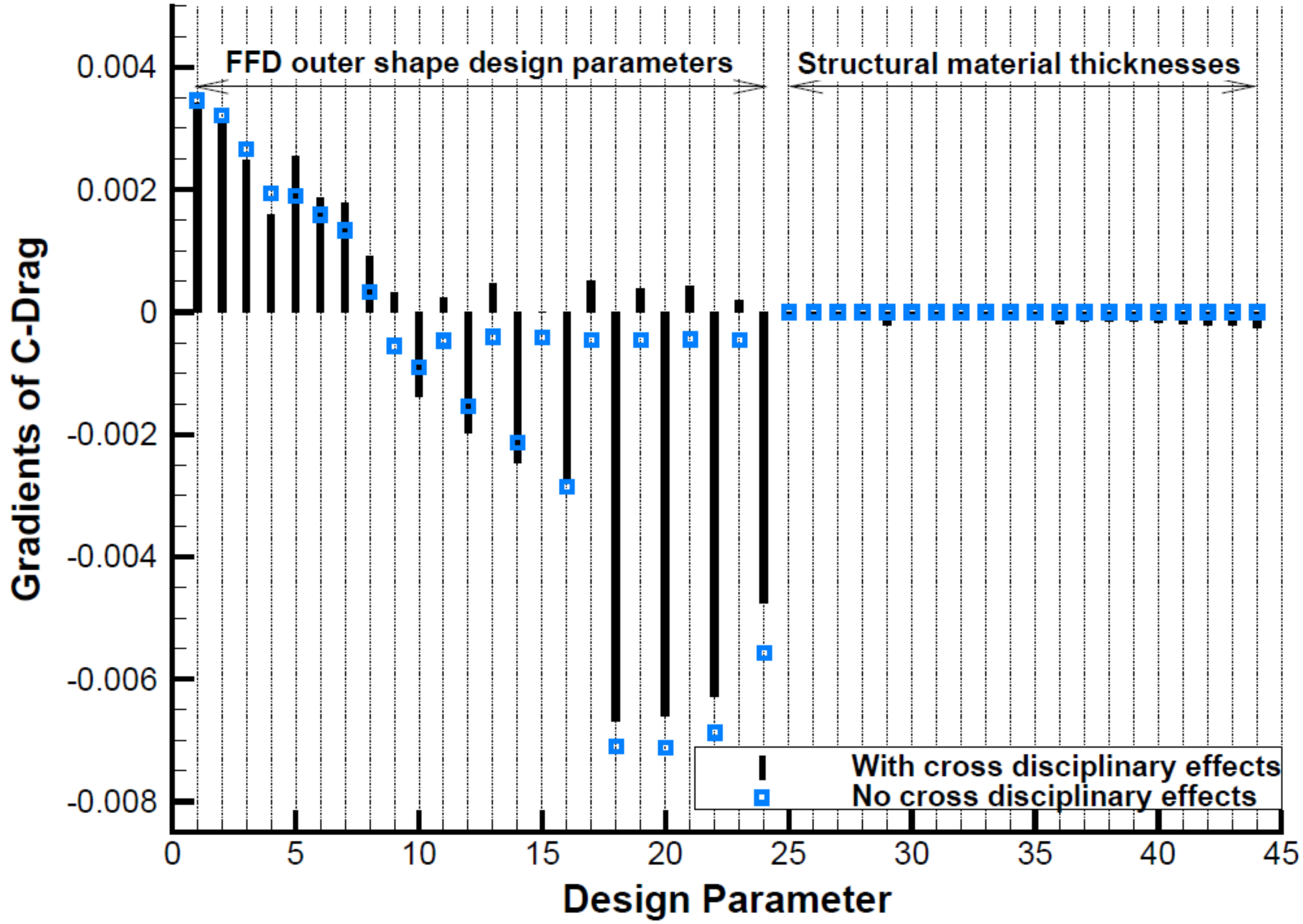
➤ Test case definition:

- A generic transport aircraft (XRF1)
- Identify the critical/sizing aerodynamic maneuver load cases

➤ *Now that we tried our best to come close to the aerostructural problem definition, we compute the gradients of all objectives and constraints (drag, lift, pitching moment, mass, structural constraints) with respect to all design variables (profile FFD and structural thicknesses)*

Aero-Structure Optimization Problem

➢ Gradients magnitudes of <u>performance part</u> of the problem:



Aero-Structure Optimization Problem

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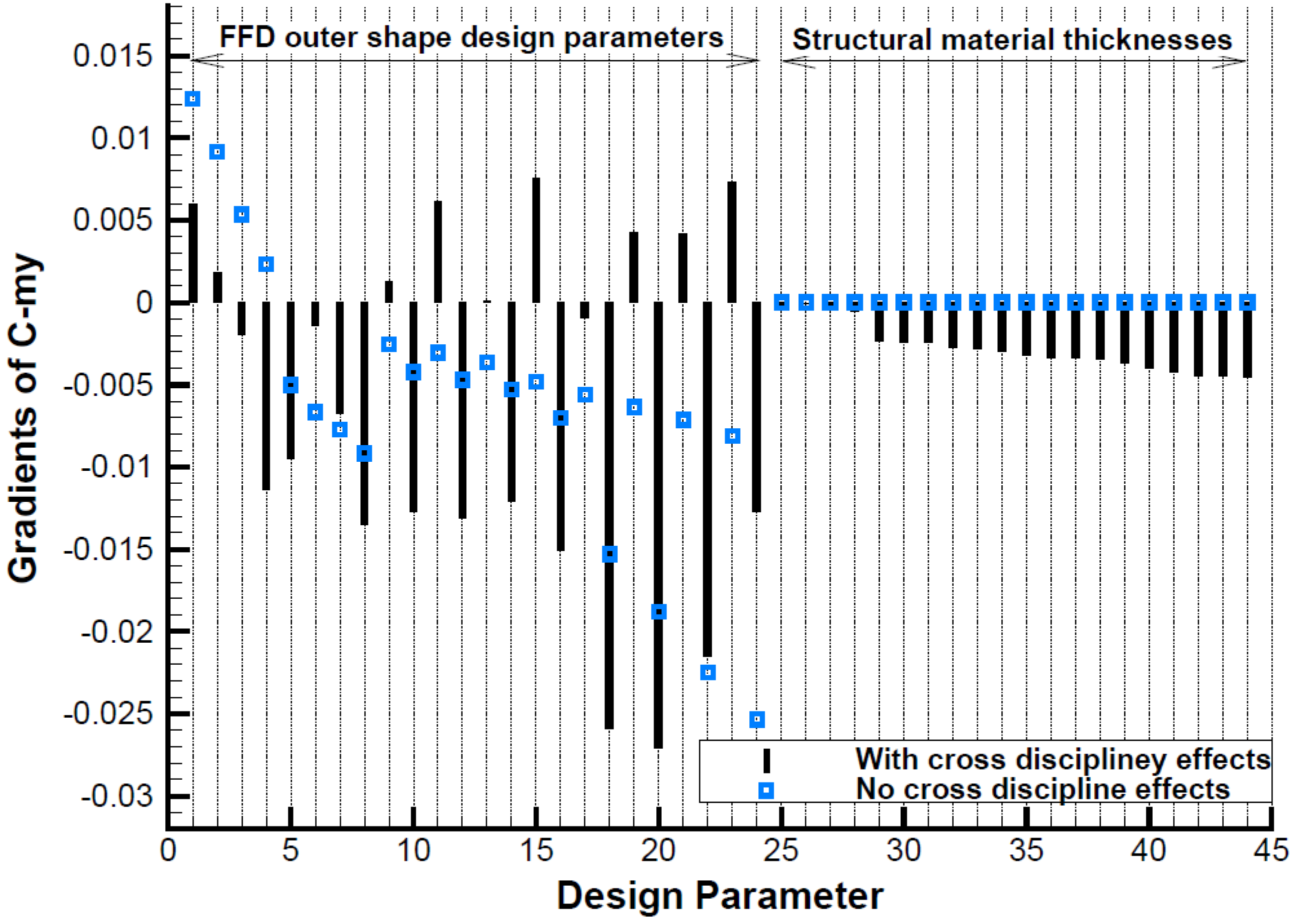
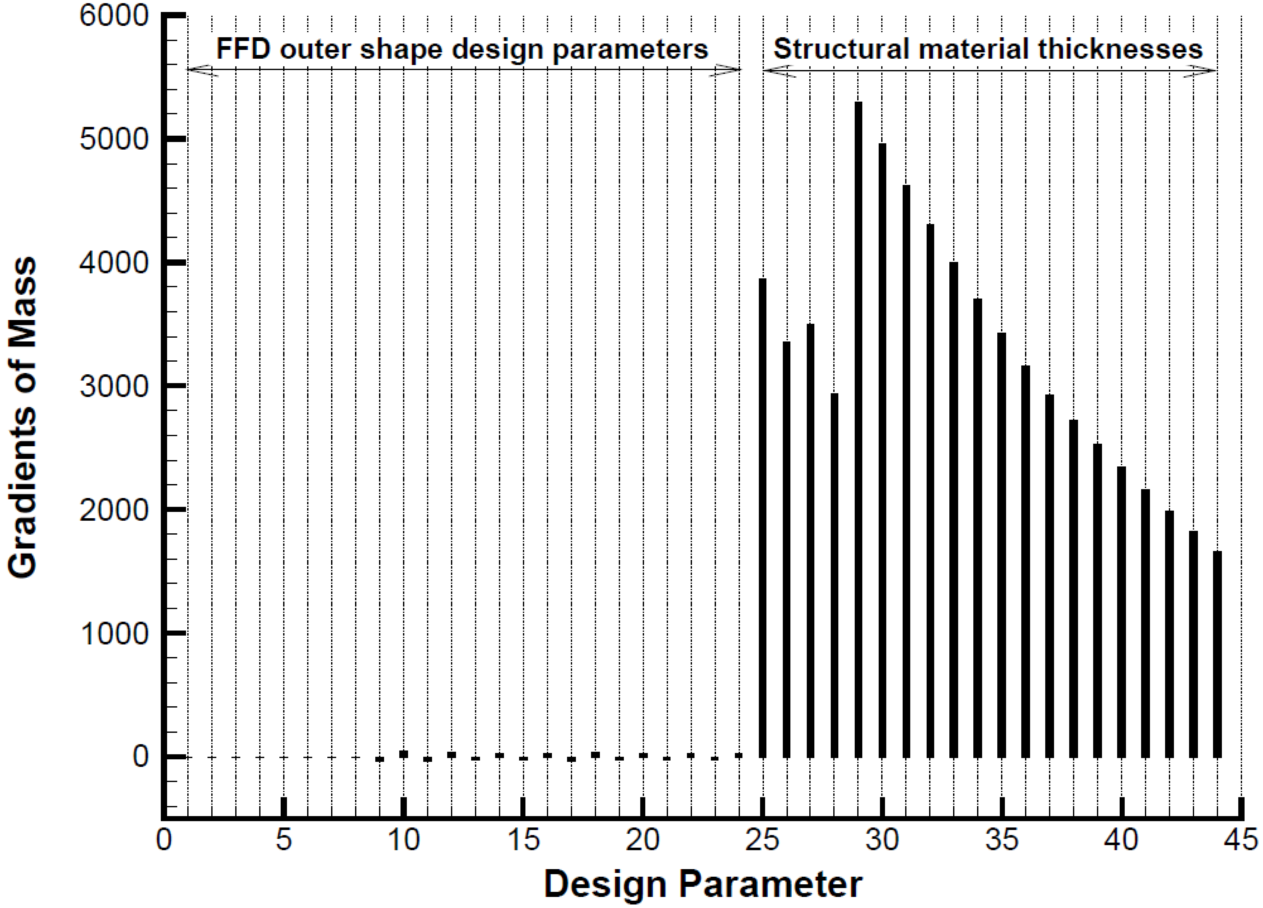


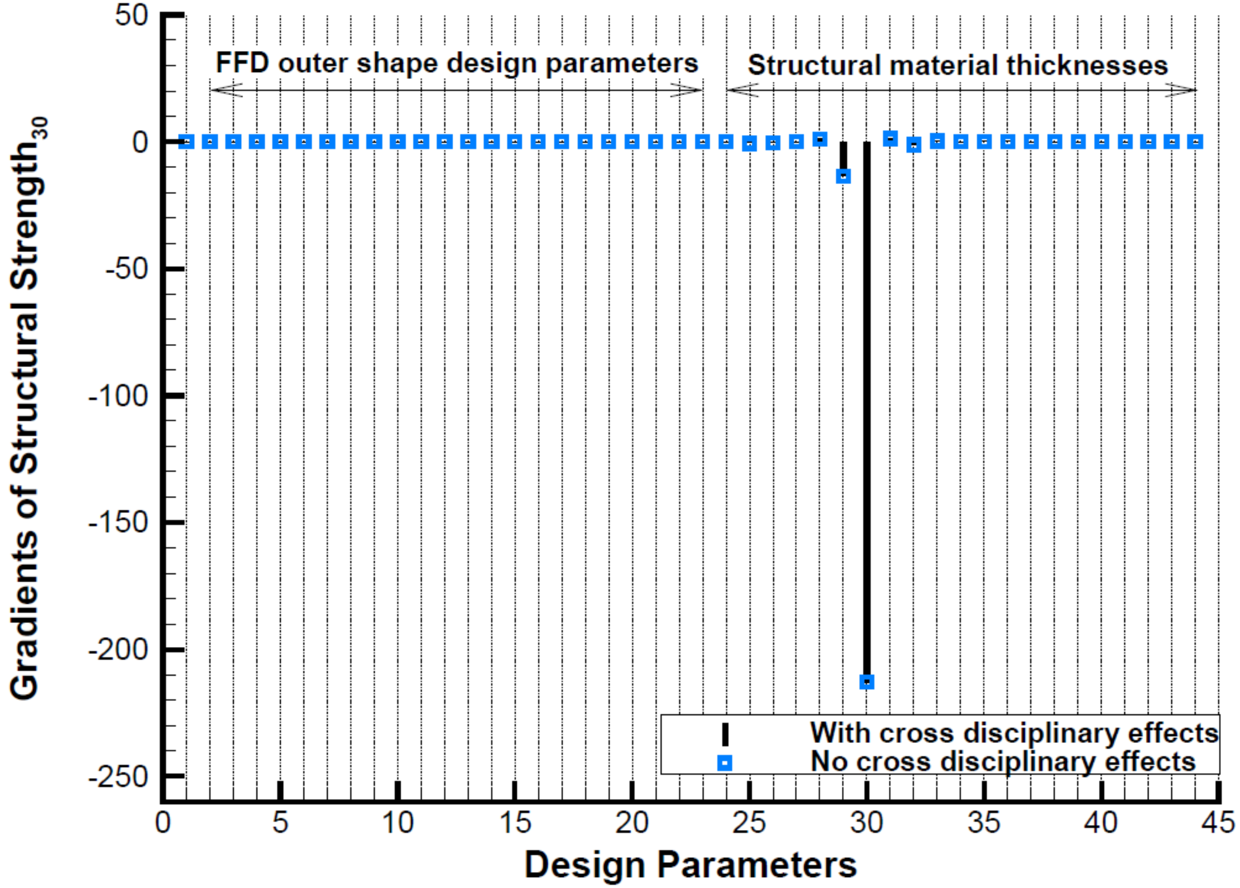
Aero-Structure Optimization Problem

- Gradients magnitudes of <u>performance part</u> of the problem:



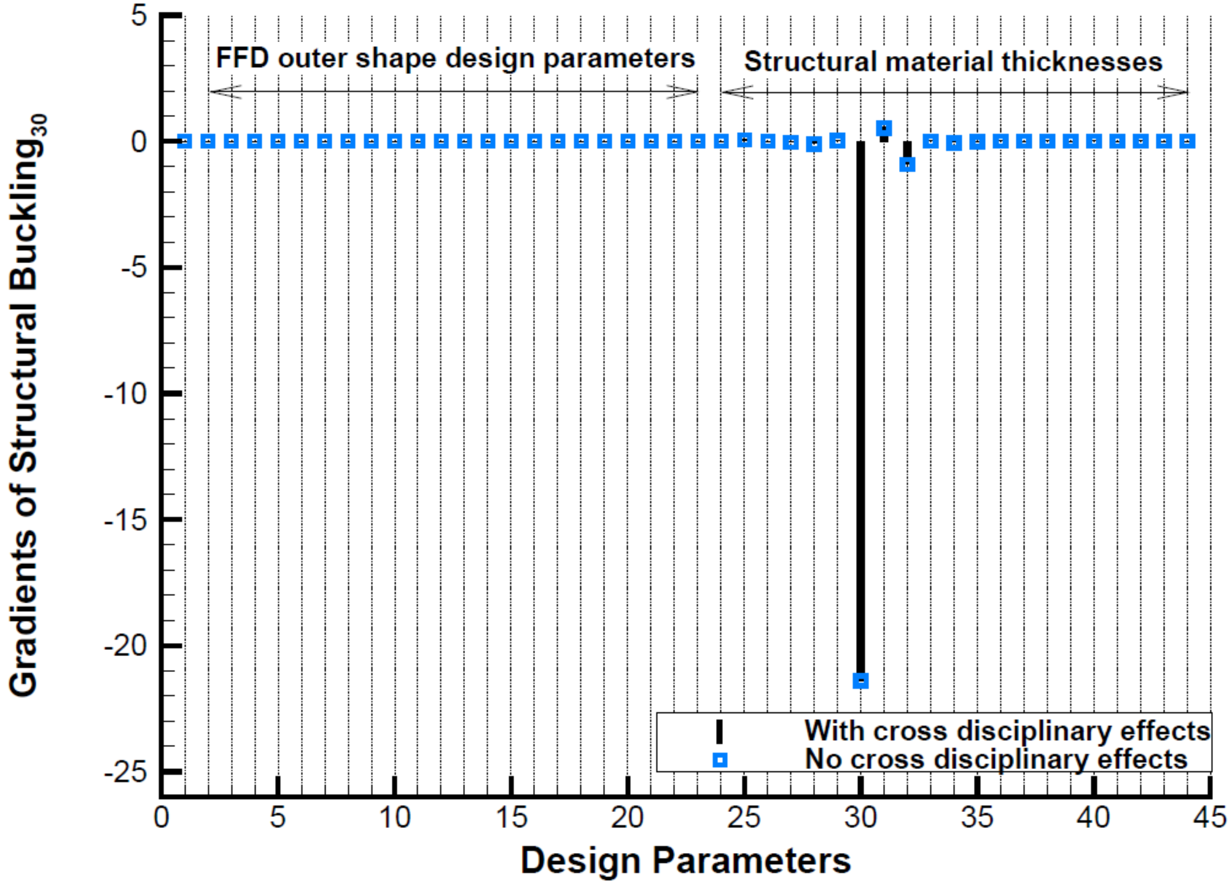
Aero-Structure Optimization Problem

➢ Gradients magnitudes of structure sizing part of the problem:



Aero-Structure Optimization Problem

➢ Gradients magnitudes of <u>structure sizing part</u> of the problem:



Aero-Structure Optimization Problem

- Based on the results of the gradient-magnitude study, three optimizations are performed
  - **Optimization that computes the full set of gradients and the full set of constraints**
    (very costly, impractical, but serves as the REFERENCE)
  - **Optimization that computes the full set of gradients but with aggregated set of constraints**
    (coupled aerostructure adjoint can be used on both sides of the problem)
  - **Optimization that computes the full set of gradients on performance side and neglects the cross disciplinary effects on the structure sizing side (while including the full set of structural constraints).**
    (Coupled aerostructure adjoint on Performance side,
    Efficient parallel FD for structure sizing side)

Aero-Structure Optimization Problem

- XRF-1 wing-body configuration

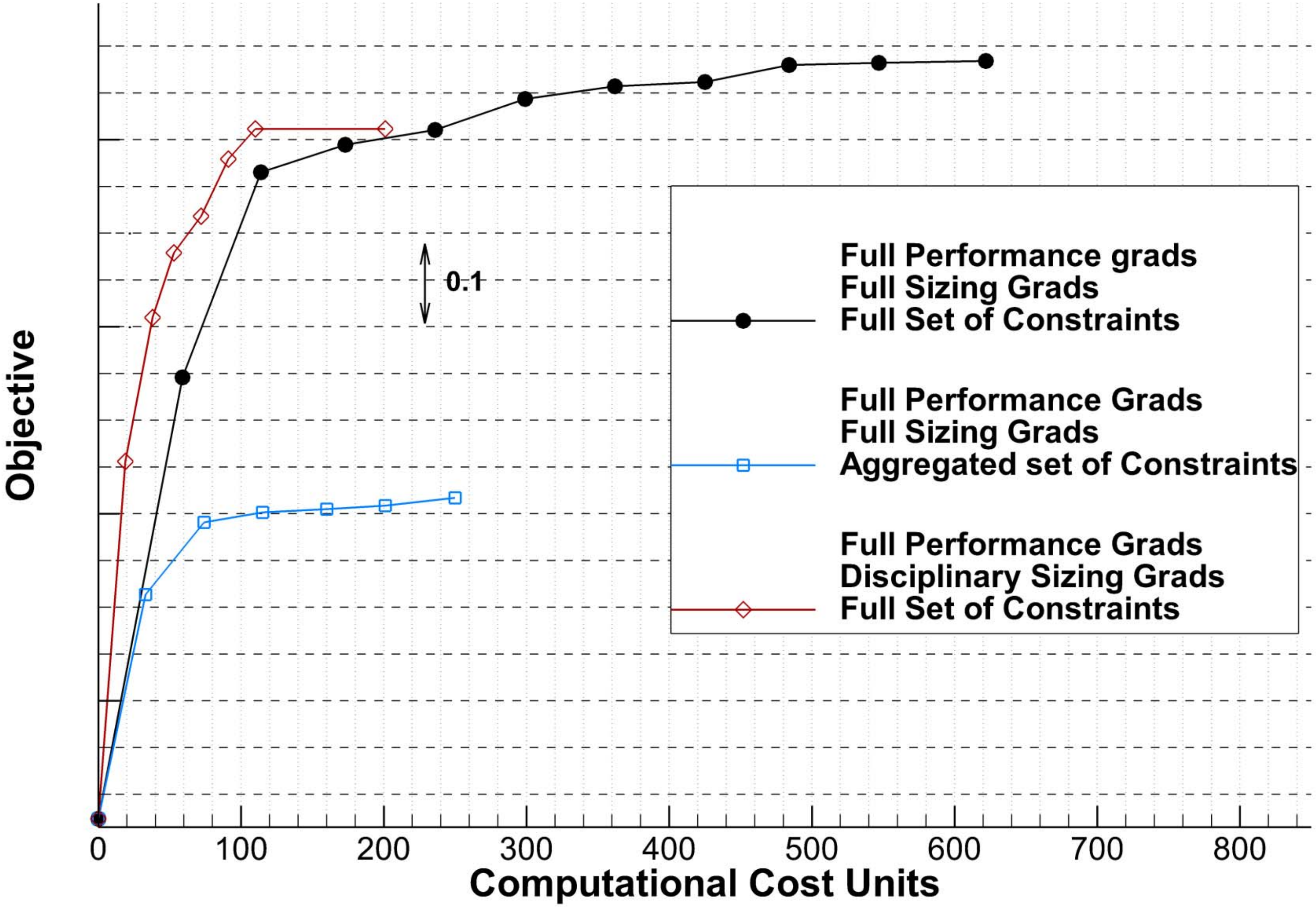
- Optimize the wing for the following objective:
  - $Objective = \frac{1}{C_W} * \frac{C_L}{C_D}$, where $C_W = \frac{Current\ structural\ mass}{reference\ mass}$

- <u>Computed points per design iteration</u>:
  - 7 critical load cases (sizing 95% of the wing) (out of 12)
  - 1 cruise (Ma=0.83, C_L=0.5)

- <u>Constraints</u>:
  - Invisible to optimizer (internal coupling iteration): lift coefficient
  - Handled by optimizer: pitching moment coefficient, strength, buckling

- <u>Computational Power:</u>
  - 192 cores

Aero-Structure Optimizations



Aero-Structure Optimization Problem

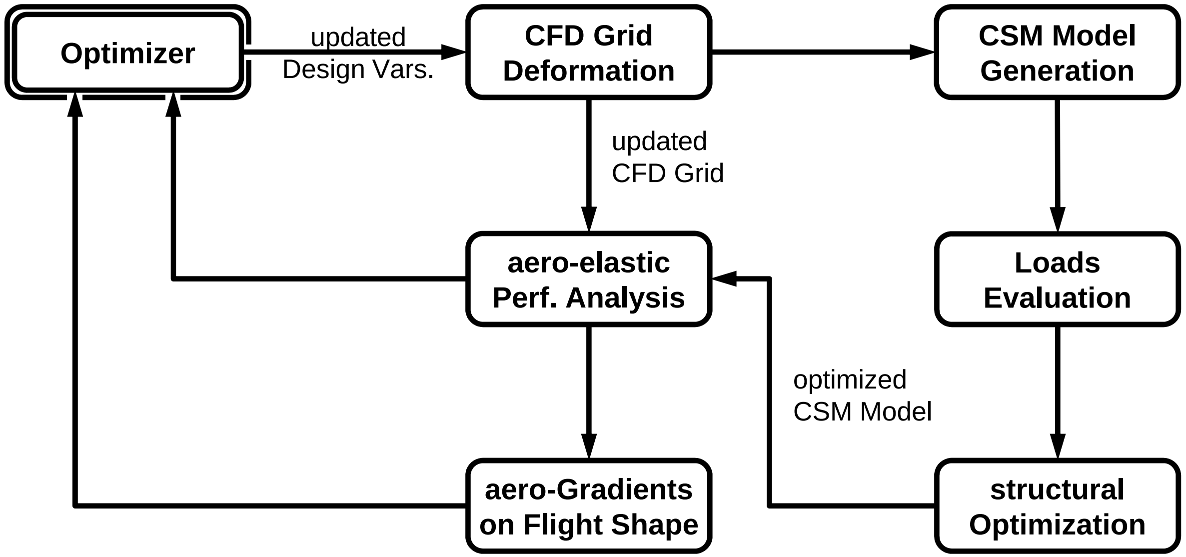
- **Suggested Solution**

  - Compute the load envelope for the baseline configuration and include not only the sizing loads but also a group of loads that are close to the sizing ones and may easily become sizing depending on which way the optimizer goes

  - Compare this to an optimization where the load envelope is computed after each step. → one descent step followed by load computation

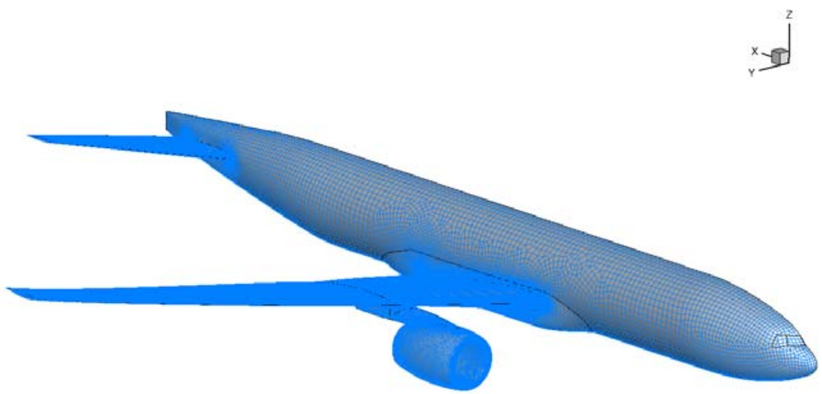
Aero-Structure Optimization Problem

➢ **First Steps in this direction**



Aero-Structure Optimization Problem

➢ First Steps in this direction

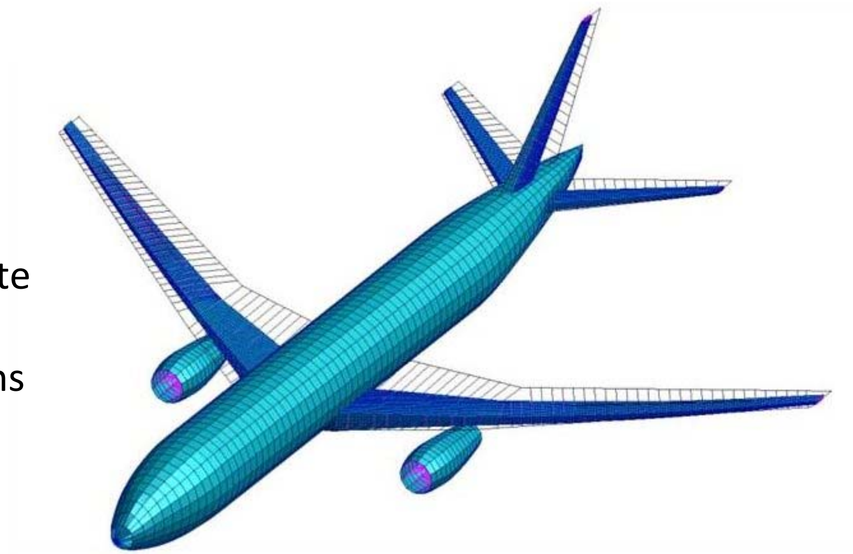


CFD Grid:

- **unstructured, hex-dominated RANS Grid.**
- **Compliant to DPW-6 Gridding Guidelines.**
- **Overall Grid Size reduced to make Grid suitable for Optimization.**
- **~7.0×10^6 Points, 43 Boundary Layers.**

Structural Model:

- **Fully automated, NASTRAN®-based Finite-Element Model Generator, including:**
  - condensed Finite-Element and DLM aerodynamic Models (⇨ enables to investigate large Number of Load Cases),
  - Loads Analysis for various Mass Configurations and Flight Conditions,
  - gradient-based structural Optimization.
- **Full Model has 143,100 Degrees-of-Freedom.**



Aero-Structure Optimization Problem

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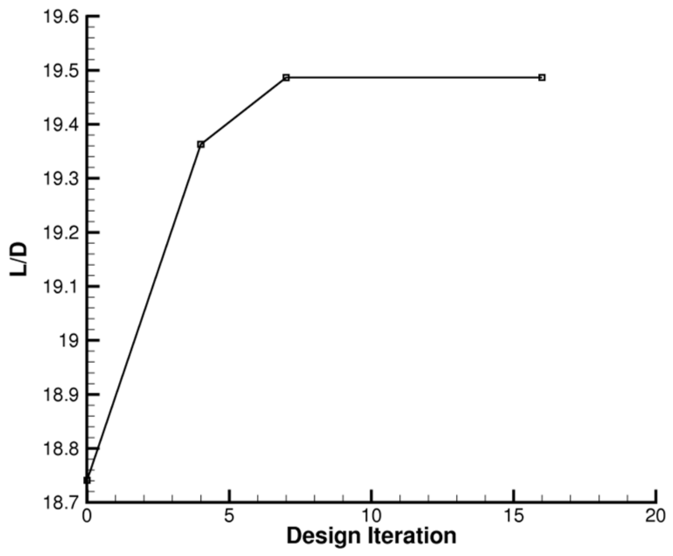
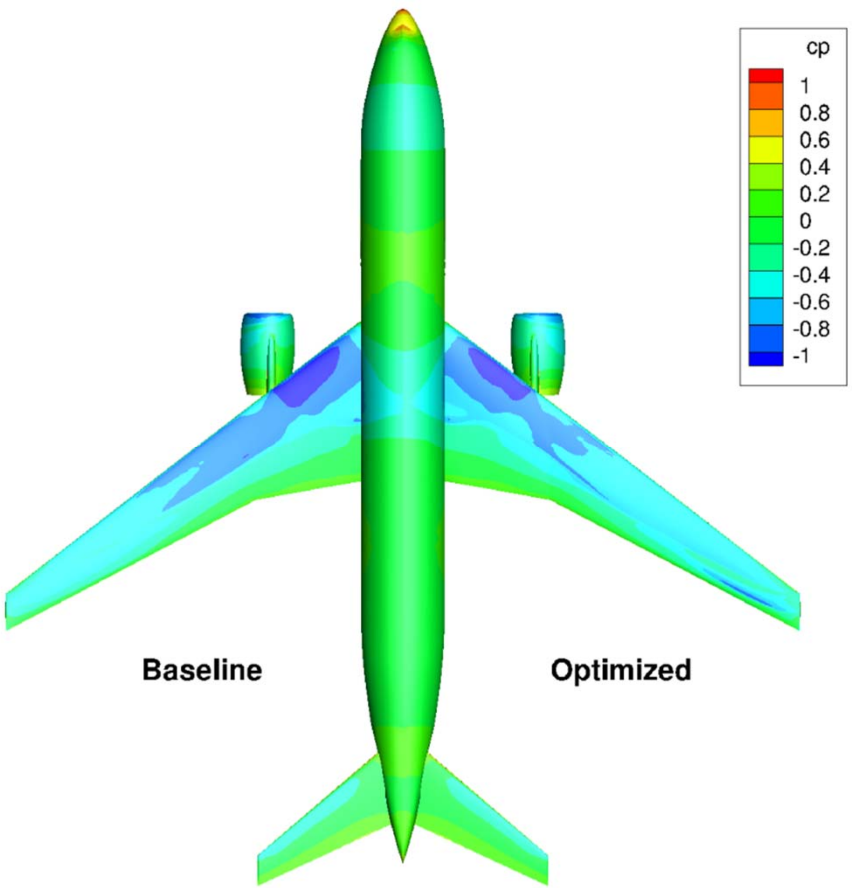




- **Only those Data Points with Drag Reduction over Baseline shown.**
- **Total Drag reduced from 285.8dc to 274.9dc (- 10.9dc), 16 Iterations.**
- **Largest Reduction over first Optimization Cycle.**

Disciplinary Gradient Capabilities (Outlook)

Structural Optimization of Composites

Structural and aeroelastic optimization of fiber composite wings with the consideration of aeroelastic constraints, modelling the structure with shell elements in MSC NASTRAN

$$A = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ & A_{22} & A_{23} \\ sym. & & A_{33} \end{bmatrix}, \quad D = \begin{bmatrix} D_{11} & D_{12} & D_{13} \\ & D_{22} & D_{23} \\ sym. & & D_{33} \end{bmatrix}, \quad h$$

<u>Continuous stiffness optimization</u>

- design variables: **A**, **D**, h → lamination parameter (LP)
- result: optimal stiffness distribution

Step 1

- Parametric model set-up
- Structural, aerodynamic, optimization model

Step 2

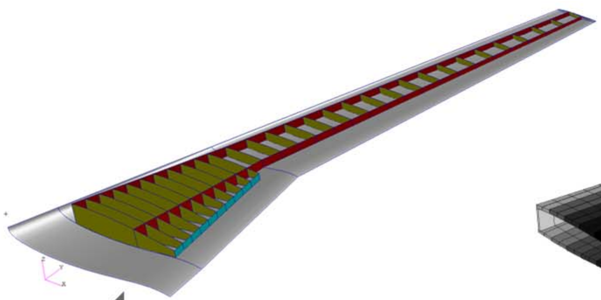
- Loads analysis
- Nastran DLM with CFD-based correction

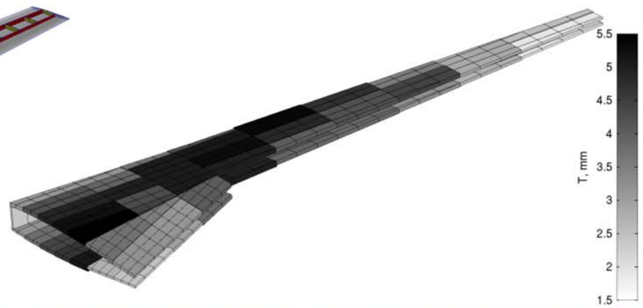
Step 3

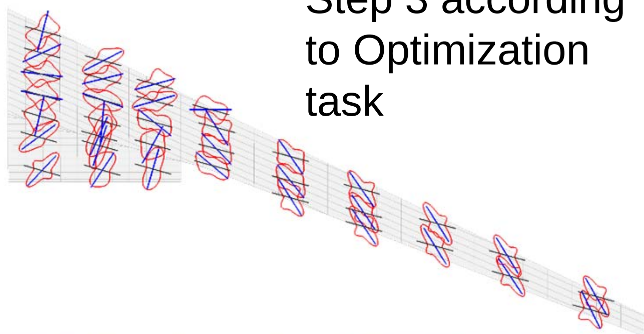
- Sensitivity Analysis
- MSC Nastran Sol 200
- External buckling analysis

Step 4

- Optimization Step
- MatLab Optimizer with LP
- Go to Step 2 or Step 3 according to Optimization task

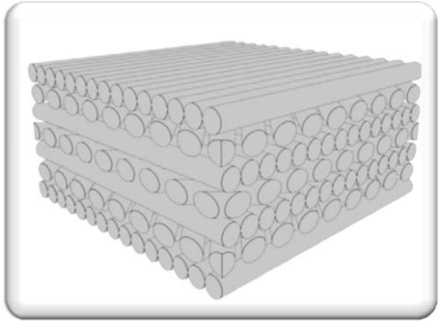






Disciplinary Gradient Capabilities (Outlook)

Detailed Structural Optimization of Composites (ongoing work)



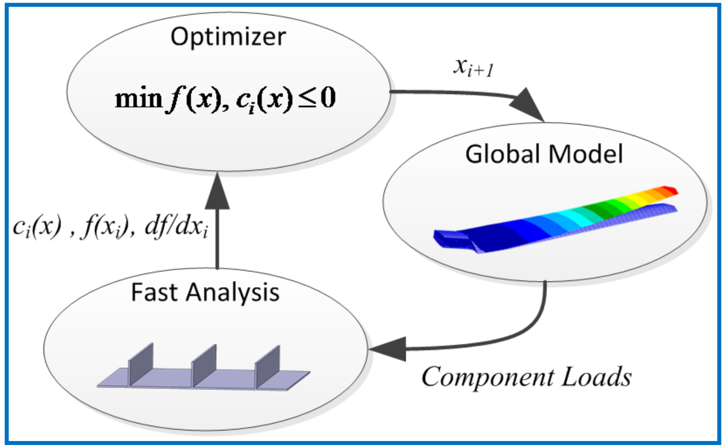
- In Composites:
  - Huge design space
  - Discrete nature of materials
  - Lots of constraints

→ Continuous and convex formulation of lamination parameters

- Complex geometry model generation (stringer modelling)

→ Stringer stiffness smeared into panel representation and validated

- Implementation in Optimization Environment
  - Highly parallel
  - Static strength criteria (buckling, column buckling, strength, damage tolerance)
  - Consideration of manufacturing criteria (i.e. ply continuity) including gradient calculation



Contents

Conclusions

- more study is needed to understand the interaction between changes in design parameters and the changes in the critical load cases.

- Setting a realistic test case is important for making conclusions, model problems will not work (different test case, like BWB, may need different approximations)

- Constraints aggregation with full set of gradients doesn't necessarily give better design than the engaging the full set of constraints with partial set (approximate) of gradients

- Including the loads process in gradient-based MDO requires more attention from the MDO community. Most of the attention in literature has been poured on the performance side of the problem.

THANK YOU FOR YOUR ATTENTION