Numerical Optimization Methods in the Aerospace Design Process
- Civil and Military Applications and Benefits -

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• The Optimization Assisted MAS Design Process
  ➢ Motivation & Process Overview
  ➢ Multidisciplinary Design Optimization Procedure LAGRANGE
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# Introduction: EADS

**European Aeronautics Defence and Space Company**

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**MILITARY AIR SYSTEMS**

- Barracuda
- Eurofighter
- Meteor
- EuroHawk
- C3I Systems
- Captor

**DEFENCE ELECTRONICS**

- A400M
- C295
- CN235
- C212
- Tiger
- NH90
- EC725
- EC135
- EC145
- EC225
- Ariane 5
- ATV
- Helios II
- Skynet 5
- Inmarsat
- Galileo

**DEFENCE AND COMMUNICATIONS SYSTEMS**

**MBDA**
Introduction: MAS Programs and Products

Combat Air Systems
- Eurofighter

Mission Air Systems
- EuroHawk
- Advanced UAV
- SIDM
- CL-289
- Tracker
- A400M

Technologies e.g.
- UCAV/ETAP
- UAV Dem.

Services
- Upgrades/MRO/CPS for various aircraft types
  - Tornado
  - F-4
  - EF-18
  - F-5 Tiger
  - Eurofighter
  - AWACS

Aerostructures
- Preferred supplier for Airbus products
- A380
- Airbus single-aisle
- Airbus wide-body
- A400M

Training Services
- ASTA
- Pilottraining
- Training Operations

Air Defence Training
- DO-DT Family
- DO-SK6

transferred to EADS Premium Aerotech, founded 1. Sep. 2008
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- Outlook and Conclusions
Motivation
The classical problem in aircraft development

- **Concept Phase**
  - Weight Problem !!!
- **Pre Design Phase**
  - “Optimisation” of Details:
    - High Effort & Cost
    - Expensive Materials
    - Small Weight Benefits
- **Detail Design Phase**
  - Weight Problem !!!
  - Mass Task Force !
- **Change of Concept**:
  - Very high effort
  - Significant Time Slip
  - Trial & Error Principle

Motivation
The classical problem in aircraft development
Dilemma of the design process

- Major decisions for the design concept have to be made in the early design phases when very little knowledge exists about the design. Only small design changes are possible in later design phases due to time and budget constraints.

- The technical performance and the cost are dominated by the early concept decisions.
Motivation
Challenges and Opportunities

Challenges:
- The technical complexities are continuously increasing with each new aircraft project
- The development times are continuously reduced with new projects
- There is not enough time to develop sufficient technical know-how about complex, multidisciplinary interactions early enough within the projects

Opportunities
- **Numerical simulation** methods allow to **analyse and understand** complex technical interactions early in the design process
- **Numerical concept optimization methods** allow to **determine optimum design concepts** in early design phases
- **Numerical parameter optimization methods** allow to **improve the product performance** (e.g. by weight reduction) and simultaneously to **reduce time and cost** in all design phases!
Automation of the structural design process by optimization methods

- **Design Concept**
- **Analysis models**
- **Structural responses**

? Design Criteria fulfilled

- yes
- no

Definition of Design modifications:
- Based on mathematical optimization criteria

- Change of Sizes & Material
- Automatic Model Update (Parameter Optimization)

- Change of Concept
- Automatic Model Update by change of material distribution (Topology Optimization)

- Change of Manual Process (very high effort)
- Change of Sizes & Material Manual Process (high effort)

Based on mathematical optimization criteria

- • Automation / Iterative process handled by the software
- • Computer controlled iteration until optimum is achieved

Final Design
The Design Task formulated as Mathematical Optimization Problem:

\[
\min \{ \ f(x) \mid g(x) \geq 0 ; \ x_l \leq x \leq x_u \}\]

- \( f \) objective function (weight)
- \( x \) vector of design variables (DV)
- \( g \) vector of constraints

- Topology Optimization: \( f = \) Compliance; \( g: \) mass, displacement const.
- Sizing Optimization: \( f = \) Weight; \( g = \) full set of design constraints (strength, fatigue, buckling, flutter,...)
Process Overview

- **Design Space (e.g. Loft, Cargo)**

- **Topology Optimisation**
  - Optimum Load Paths and Material Distribution
  - Structural Concept Clues

- **Validated Stress & Strength Methodologies and Tools**
  - In-house Tool LAGRANGE

- **Engineering Design Concept**
  - Topology Results Understanding & Interpretation
  - Concept Development considering additional engineering requirements (buckling, damage tolerance...)

- **Engineering Team**

- **Structural Optimisation**
  - Dimension and Shape of Structural Members
  - HyperMesh (Pre- & Postpr.)

- **CAE Detailed Analysis and Verification**
  - Geometric Modelling - Detailed Design

- **CAD**
  - Geometric Modelling - Detailed Design

- **Final Part Testing and Certification**
  - HyperMesh (Pre & Postprocessing F2K etc.)

- **Manufacturing Realised Part**

- **HyperMesh OptiStruct**

- **Structural Design Criteria**
Multidisciplinary Design Optimization Procedure LAGRANGE

1. FEM
   Statics, Dynamics, Buckling, Aeroelast.

2. Aerodynamics
   Doublet Lattice, Higher Order Methods (HISSS)

3. Skill Tools
   Analytical, semi-empirical methods for Strength & Failure Criteria, Buckling, Postbuckling, etc.

More than 120 man-years of development since 1984!

Optimization Model

- Initial design: \( y^0 \) @ \( x^0 \)
- Design model: \( y(x) \)
- Structural analysis model: \( y^c = \text{const.} \)
- Evaluation model: \( f(r(y(x))), g(r(y(x))) \)
- Sensitivity analysis: \( \frac{\partial f}{\partial x}, \frac{\partial g}{\partial x} \)
- Optimization algorithms

Convergence? Yes → \( x^* \)

No → \( x^+ \)

Optimal design: \( x^* \)

Fully analytical sensitivities for large scale problems
### Multidisciplinary Analysis Models and Responses

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<tr>
<th>FE-Model</th>
<th>Aerodyn. Model</th>
<th>Fiber-Courses</th>
<th>Ply Distribution</th>
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#### Analysis Models and Responses

- **STATICS**
  - displacements, stresses, strains, failure criteria, anisotropic buckling, postbuckling

- **DYNAMICS**
  - eigenvalues, eigenmodes, frequency res., transient res.

- **STEADY AEROELASTICS**
  - displacements, aeroelast. loads effectiveness, stress / strain criteria, buckling

- **FLUTTER**
  - flutter speeds, flutter frequenc., flutter modes, damping

- **MANUFACTURING**
  - drop off angles, course curvatures, tape shearing

**multidisciplinary responses and sensitivities w.r.t. design variables**
Multilevel analysis approach

1st Level: Global Analysis of Static and Dynamic Behaviour:

a) Static Finite Element Analysis with prescribed external loads:

\[ K \cdot u_L = f_L \]

b) Aeroelastic Analysis for steady state manoeuvres:

\[ [K - C] \cdot u_T = f_0 + g \]

d) Flutter Analysis:

\[ [K - C + \omega^2 M] \cdot q = 0 \]

c) Manufacturing Analysis: e.g. Tape-Laying / Fiber Placement

2nd Level: Local Analysis of Substructures:

a) Local Stability and Postbuckling Analysis based on analytical solutions:

(various, design dependent solutions have to be applied in order to cover all potential stability phenomena of skin, stringers, webs and other substructures)

b) Local FE-Stability Analysis on substructure level:

\[ [K_S + \lambda K_S g(u_L)] \cdot u_S = 0 \]

c) Local stress/strain analysis (from global static or aeroel. results):

\[ \varepsilon = T \cdot B \cdot u_e \]

d) Local tape shearing / fiber curvature analysis ……. 

3rd Level: Local Strength and Failure Assessment
• Determination of weight optimum concepts, shapes and sizes
• Optimum performance of very advanced products requiring the consideration of complex, multidisciplinary relations and interactions
• Reduced effort, time & cost by avoiding late concept changes
• Reduced effort, time & cost by the automation of the design process
• Very important: Optimization process has to be an integral part of the design process. It does not make sense to start it at the end !!!
• Technical Challenges
  - Complex in-house analysis procedures for stability, strength, repairability etc. are required for aerospace structures. These in-house procedures need to be integrated in the design optimization process in order to determine a feasible design solution satisfying all requirements simultaneously!
  - The huge number of design freedoms for composite structures (number of plies, stacking sequence, fiber orientations) results in very large numbers of design variables and constraints
  - Analytical sensitivities, large scale & parallelization methods are required for these problems. However, this requires a lot of development efforts.

• Non-Technical challenges
  - there is a lack of trained experts in Numerical Optimization Techniques
  - there is lack of management awareness and know-how about optimization
  - Very complex work-shares with a huge number of (competing) partners and subcontractors create additional obstacles
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Topology and Sizing Optimization of the A380 Inner Leading Edge Ribs

CAD-Model

Prototype

A380 Inner Leading Edge

Sizing Optimization

Topology Optimization

Interpretation

RESULTS: 6-
THICKNESS DISTRIB.
LAYER NUMBER = 1
UNKNOWN SCALAR - MAG MIN: 1.00E+00 MAX: 3.26E+00 VALUE OPTION: ACTUAL SHELL
SURFACE: TOP CRITERION: ABOVE : 1.00E+00

1.00E+00
1.23E+00
1.45E+00
1.68E+00
1.90E+00
2.13E+00
2.36E+00
2.58E+00
2.81E+00
3.03E+00
3.26E+00

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Prototype of the A380 Inner Leading Edge
A350 Fuselage Tail Section 19

Topology Optimization

Part

Manufacturing
Realised Part

CAE
Detailed Analysis and Verification

CAD
Geometry Model

Design Concept

Conceptual Sizing Optimization

Design Space

3D-Topology

ca. 15 - 20% weight saving purely due to new concept
A400M Cargo Door

Concept Optimization

Part

Manufacturing
Realised Part

CAE
Detailed Analysis and Verification

CAD
Geometry Model

Composite Sizing Optimization

3D Topology

2D-Topology

Design Concept
A400M First Cargo Door (CFRP + Alu side beams)
Principal aeroelastic effects versus primary stiffness axes

- Manoeuvre drag reduction
- Manoeuvre load relief
- Lift effectiveness
- Control effectiveness
- Flutter prevention
- Divergence protection
- Maneuver load relief
- Maneuver drag reduction
- Lift effectiveness
- Control effectiveness
- Flutter prevention
- Divergence protection


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Aeroelastic Tailoring of the A350 XWB Wing Box

Aerodynamics Model

Finite Element Model
19 Ground & Aeroelastic Manouevre Load cases

Optimization Model:
• 700 – 3000 Design Variables
  - Ply-Thicknesses
  - Fiber Orientations
  - Stringer Cross Sec.

• > 300,000 Constraints:
  - Skin Buckling
  - Column Buckling
  - Strength
  - Manufacturing

More than 40 Design Optimization Studies performed by 3 people within 6 month
A350 XWB Flap Support Structure

Concept Development and subsequent Sizing Optimization ongoing

3D-Topology Optimization Result
A350 XWB Composite Front Fuselage Section

- Current Project: Composite Fuselage Sizing
  - more than 14000 design variables
    (skin-lay-up, stringer-geometry & lay-up)
  - more than 1,000,000 constraints
  - Decomposition of the optimization problem because of the large number of design variables
Summary

• Optimization assisted design process has been established and applied within all Design Phases of a broad range of A/C projects (civil and military applications; components, large assemblies and full A/C)

• HyperMesh & OptiStruct are intensively used for Pre-& Postprocessing as well as Topology Optimization

• Consideration of various Multidisciplinary Design Criteria (strength, stability, postbuckling, dynamics, aeroelastics, manoeuvre & gust loads, manufacturing) within the MAS numerical optimization tool LAGRANGE

• Strategic EADS-MAS decision for an in-house MDO tool because of specific aerospace design criteria (no Commercial Of The Shelf tool available) and full adaptability to advanced analysis methods as well as new technological product and customer requirements

Automation of the design process by optimization methods saves weight, time & cost !!!