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

Dr. Gerd Schuhmacher
Manager Optimization and Special Analysis
EADS Defence and Security, Military Air Systems (MAS), Manching - Germany
Gerd.Schuhmacher@eads.com
Contents

• Introduction

• The Optimization Assisted MAS Design Process
  ➢ Motivation & Process Overview
  ➢ Multidisciplinary Design Optimization Procedure LAGRANGE
  ➢ Application Phases, Benefits & Challenges

• Applications

• Summary
# Introduction: EADS

**European Aeronautics Defence and Space Company**

<table>
<thead>
<tr>
<th>Airbus</th>
<th>Military Transport Aircraft</th>
<th>Eurocopter</th>
<th>Space</th>
<th>Defence &amp; Security Systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>A380</td>
<td>A400M</td>
<td>Tiger</td>
<td>Ariane 5</td>
<td>Barracuda</td>
</tr>
<tr>
<td>A350 XWB</td>
<td>C295</td>
<td>NH90</td>
<td>ATV</td>
<td>Eurofighter</td>
</tr>
<tr>
<td>A340</td>
<td>CN235</td>
<td>EC725</td>
<td>Helios II</td>
<td>Meteor</td>
</tr>
<tr>
<td>A330</td>
<td>C212</td>
<td>EC135</td>
<td>Skynet 5</td>
<td>EuroHawk</td>
</tr>
<tr>
<td>A318/319/320</td>
<td></td>
<td>EC145</td>
<td>Inmarsat</td>
<td>C³ Systems</td>
</tr>
<tr>
<td>A300-600 F</td>
<td></td>
<td>EC225</td>
<td>Galileo</td>
<td>Captor</td>
</tr>
</tbody>
</table>

**Military Air Systems**

**Defence Electronics**

**Defence and Communications Systems**

**MBDA**
# Introduction: MAS Programs and Products

## Combat Air Systems
- Eurofighter

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

### SUZ Eurofighter/Tornado
### Training Services
- ASTA
- Pilottraining
- Training Operations

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

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

---

Transferred to EADS Premium Aerotech, founded 1. Sep. 2008
Contents

• Introduction

• The Optimization Assisted MAS Design Process
  ➢ Motivation & Process Overview
  ➢ Multidisciplinary Design Optimization Procedure LAGRANGE
  ➢ Application Phases, Benefits & Challenges

• Applications

• Outlook and Conclusions
The classical problem in aircraft development

**Motivation**

- Concept Phase
- Pre Design Phase
- Detail Design Phase

**Weight Problem !!!**

- "Optimisation" of Details:
  - High Effort & Cost
  - Expensive Materials
  - Small Weight Benefits

**Change of Concept:**

- Very high effort
- Significant Time Slip
- Trial & Error Principle

**Weight Problem !!!**

Mass Task Force!
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.
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!
The traditional, iterative structural design process

- Design Concept
- Analysis models
- Structural responses

? Design Criteria fulfilled

yes

Final Design

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

Definition of Design modifications:
- based on experiences,
- “fully stressed design”,
- “heuristic”, etc.

- Manual, experience based process
- Limited number of iterations
Automation of the structural design process by optimization methods

- Design Concept → Analysis models → Structural responses

  - ?
  - Design Criteria fulfilled
    - yes → Final Design
    - 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)

  - • Automation / Iterative process handled by the software
  - • Computer controlled iteration until optimum is achieved
The Design Task formulated as Mathematical Optimization Problem:

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

- **f** objective function (weight)
- **g** vector of constraints
- **x** vector of design variables (DV)
- **x_l** lower bound of DV
- **x_u** upper bound of DV

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

Design Space (e.g. Loft, Cargo)

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

Structural Optimisation
- Dimension and Shape of Structural Members
  - HyperMesh (Pre & Postprocessing)
  - In-house Tool LAGRANGE

Validated Stress & Strength Methodologies and Tools

Engineering Team

Topography Optimisation
- Optimum Load Paths and Material Distribution
- Structural Concept Clues

CAD
- Geometric Modelling - Detailed Design

CAE
Detailed Analysis and Verification

Final Part Testing and Certification

Manufacturing Realised Part

HyperMesh
OptiStruct

Structural Design Criteria

© EADS 2008 – All rights reserved
Multidisciplinary Design Optimization
Procedure LAGRANGE

Optimization Model

- initial design \( y^0 \) ® \( x^0 \)
- design model \( y(x) \)
- structural parameters \( y^c = \text{const.} \)

convergence?

- yes
  - optimal design \( x^* \)
- no
  - optimization algorithms
  - sensitivity analysis
    - \( \frac{\partial f}{\partial x}, \frac{\partial g}{\partial x} \)
  - evaluation model
    - \( f(r(y(x))) \)
    - \( g(r(y(x))) \)
  - structural analysis model
    - \( r(y, y^c) \)

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!**
## Analysis Models for Multidisciplinary Optimization

### Multidisciplinary Analysis Models and Responses

<table>
<thead>
<tr>
<th>FE-Model</th>
<th>Aerodyn. Model</th>
<th>Fiber-Courses</th>
<th>Ply Distribution</th>
</tr>
</thead>
</table>

#### 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: \( [K_S + \lambda K_S g(u_D)] \cdot u_S = 0 \)
   c) Local stress/strain analysis (from global static or aeroel. results): \( \varepsilon_e = T \cdot B \cdot u_e \)
   d) Local tape shearing / fiber curvature analysis …….

3rd Level: Local Strength and Failure Assessment
Application Phases and Benefits

- 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 !!!**
Challenges

• 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
Contents

• Introduction

• The Optimization Assisted MAS Design Process
  ➢ Motivation & Process Overview
  ➢ Multidisciplinary Design Optimization Procedure LAGRANGE
  ➢ Application Phases, Benefits and Challenges

• Applications

• Summary
Topology and Sizing Optimization of the A380 Inner Leading Edge Ribs

Results:
- Thickness Distribution
- Layer Number: 1
- Unknown Scalar - Min: 1.00E+00, Max: 3.26E+00
- Value Option: Actual Shell Surface
- Top Criterion: Above

- Thickness Values:
  - 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
Prototype of the A380 Inner Leading Edge
A350 Fuselage Tail Section 19

Part

Manufacturing
Realised Part

CAE
Detailed Analysis and Verification

CAD
Geometry Model

Conceptual Sizing Optimization

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

Design Concept

Design Space

3D-Topology

Topology Optimization

CAE
Detailed Analysis and Verification

Conceptual Sizing Optimization

3D-Topology

Design Concept

Part

Manufacturing
Realised Part

© EADS 2008 – All rights reserved
A400M Cargo Door

Manufacturing
Realised Part

CAE
Detailed Analysis and Verification

CAD
Geometry Model

Composite Sizing Optimization

Concept Optimization

Part

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
- Divergence protection
- Flutter prevention
- Maneuvre load relief
- Divergence protection
- Lift effectiveness
- Control effectiveness

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 engineers within 6 month

© EADS 2008 – All rights reserved
A350 XWB Flap Support Structure

Concept Development and subsequent Sizing Optimization ongoing

3D-Topology Optimization Result

Design Space
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!!!