Gradient-Based Aerodynamic Optimization with the *elsA* Software

*Prepared and presented by*


*at the AIAA SciTech2014 conference, January 2014*

*Also presented by J. PETER at the ANADE Workshop  - Cambridge - September 24th 2014*
Outline

1. Introduction
2. Methods & tools
3. Test-Case 1 : NACA0012
4. Test-Case 2 : RAE2822
5. Test-Case 3 : CRM wing
6. Conclusion/Perspectives
Introduction

- Adjoint-based aerodynamic optimization capability:
  - Developed since 2000 in the elsA software (discrete adjoint)
  - Used by ONERA and Airbus for practical/industrial applications

- Three drag minimization test cases proposed by the ADO-DG were treated:
  - 2D, NACA0012, Euler, geometry constraints
  - 2D, RAE2822, RANS, lift/pitching moment/geometry constraints
  - 3D, CRM wing, RANS, lift/pitching moment/geometry constraints

- Special focus on:
  - Impact of the parameterization
  - Influence of the gradient algorithm
  - Influence of the way of formulating the optimization problem
Methods & Tools

- **elsA**: ONERA multiblock structured code
  (+TNC matches, + Overset, …)

- **ffd72**: ONERA far-field drag extraction and derivation

- Parameterization/mesh deformation:
  - SeAnDef (ONERA): volumic, parameterized, analytical mesh deformation
  - PADGE + Voldef (Airbus)

- Optimization software system:
  - In-house, Python-based
    - Dakota (SANDIA), OpenDACE (Airbus)
  - Gradient algorithms:
    - Fletcher-Reeves Conjugate Gradient (FRCG)
    - Modified Method of Feasible Directions (DOT)
    - SLSQP = sequential least square quadratic programming (PyOpt and NLopt)
Outline

1. Introduction
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3. Test-Case 1 : NACA0012
4. Test-Case 2 : RAE2822
5. Test-Case 3 : CRM wing
6. Conclusions
Test-Case 1: NACA0012 optimization

Problem statement

- Optimization problem:
  Min CD @ CL=0 and Mach=0.85
  subject to constraint: $y \geq y_{NACA0012}$

- Aerodynamic model:
  - Euler
  - JST/Roe Scheme
  - CFD meshes:
    - C-type (Rizzi)
      316 x 124
    - O-type (Vassberg & Jameson's mesh)
      256 x 256
Test-Case 1: NACA0012 optimization

Parameterization

3 types of parameterization of $\Delta y(x)$ were investigated (geom. constraint satisfied implicitly):

- B-Spline CP parameterization (6, 12)

- Hierarchy of nested Bézier-CP parameterizations (6, 12, 24, 36, 48, 64, 96): (following Vassberg’s study)

- “All grid points” parameterization ($\Delta y$)
Test-Case 1: NACA0012 optimization

Optimization results (1/2)

- Stage 1: FD-based optimizations to investigate the effect of the parameterization nature
  - B-Spline vs Bézier:
    - B-Splines are better-suited for the problem for low-dimension parameterization
  - CP distributions
    - Working on geometry modification functions allows more freedom on the CP position leading to significant improvement for a given design space dimension
    - 1 degree elevation of B-Splines provides a better performing airfoil but at the price of an increased computational cost in FD approach (more parameters more costly FD)
Test-Case 1: NACA0012 optimization

Optimization results (2/2)

- Stage 2: Adjoint-based optimizations to investigate:
  - Effect of the parameterization dimension (6, 12, 24, 36, 48, 64, 96)
    - From 6 to 48 variables, more variables yield better optima
    - In higher dimensional spaces, FRCG “stalls”. SLSQP apparently succeed to exploit high-dimensional spaces
  - Effect of gradient optimization algorithm:
    - SLSQP over-performs FRCG
Test-Case 1: NACA0012 optimization

Optimization verifications (1)

- **Similar trends** on the geometry modifications

- **Verification of optimized designs using**
  - Grid convergence study in O-type grids (up to 1024 x 1024) calculated with JST scheme (ki4=0.008)
  - Far-field drag analyses (ffd72)
Test-Case 1: NACA0012 optimization

Optimization verifications (2)
(left: far-field drag analysis – \( \text{div}(f^*) \) – of final shape)

Mesh convergence study

NACA0012: > 470 d.c.

SPL12: 84 d.c.

BEZ96+FULL: 35.5 d.c.
Test-Case 1 : NACA0012 optimization

Conclusions

• **Parameterization:**
  - Position of the CPs is important: it seems better to decouple the geometry deformations from the characteristics of initial geometry
  - Effect of dimensionality (with Bézier param.): improvement of the optimum with dimension, up to the point where problem stiffness voids the benefits…
  - “All-points” parameterization
    - Allowed further improvements of Bézier-based designs (3 to 8 d.c. improvements)
    - … but did not yield good results when started from NACA0012. Why? Smoothing?

• **Gradient algorithms:**
  - SQP performed better than FRCG (as expected) with Bézier param.
  - FRCG can be more robust with “all-points” param.
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Test-Case 2 : RAE2822 optimization

Problem statement

- Optimization problem:
  Min CD @ Mach=0.734, Re=6.5 x 10^6
  subject to constraint: CL = 0.8
  CM ≥ -0.092
  Constant Area

- Aerodynamic model:
  - RANS, Spalart-Allmaras model (frozen eddy-viscosity adjoint)
  - 2nd order Roe Scheme
  - C-Type CFD meshes:
    - For optimization:
      - multi-block mesh with 153'300 Nodes
    - For mesh convergence study:
      - hierarchy of 5 meshes with 499'004 to up to 7'894'172 Nodes

- Optimization algorithm: SLSQP
Test-Case 2 : RAE2822 optimization

Parameterization

- **Parameterization**:  
  - RAE2822 geometry approximated using B-Spline parameterization: 
  - Parameterization changes the camber line only - Thickness law is unchanged keeping the airfoil area constant during the whole optimization process (same $\Delta y$ for suction and pressure side corresponding points); 
  - The camber law is controlled by changing the vertical position of B-Spline control points, clustered in 10 groups (linking the $\Delta y$ of gathered points).
Test-Case 2: RAE2822 optimization

Optimization results (1/2)

(left plot: KKT condition states is in the subspace of active inequality constraints)

- Convergence history

- Improvements of the objective function by about 91 d.c. - All constraints respected

- Drag improvement comes from pressure part mainly, with slight penalty on friction

<table>
<thead>
<tr>
<th>Shape</th>
<th>AoA</th>
<th>CL</th>
<th>CM</th>
<th>CD</th>
<th>CDp</th>
<th>CDf</th>
<th>Area (m²)</th>
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<td>53.5</td>
<td>57.6</td>
<td>0.0779</td>
</tr>
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</table>
Test-Case 2: RAE2822 optimization

Optimization results (2/2)

- Geometry and pressure distribution:
  - The final geometry is smooth and shock free.
  - The loss of lift (consequence of the removal of the shock) has been recovered by accelerating the flow in the leading edge region.
Test-Case 2 : RAE2822 optimization

**Optimization verifications**

- **Mesh convergence study:**
  - When performing the mesh convergence study on the optimized shape, constraint on CM wasn’t anymore observed on finer meshes.
  - To overpass that issue, additional optimization steps have been performed on the extra-fine mesh to recover the CM constraint while keeping a low drag level. The final optimised shape is almost unchanged.
  - Convergence of 0.1 count is reached for lift and drag using Richardson extrapolation.
  - Final optimized shape satisfies all constraints with almost no wave drag.

### RAE2822 profile

<table>
<thead>
<tr>
<th>Mesh</th>
<th>CL</th>
<th>CM</th>
<th>CD</th>
<th>CDw</th>
</tr>
</thead>
<tbody>
<tr>
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<td>Extra-Fine</td>
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<tr>
<td>Richardson</td>
<td>-</td>
<td>-</td>
<td>189.3</td>
<td>-</td>
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</table>

### Optimized Shape

<table>
<thead>
<tr>
<th>Mesh</th>
<th>CL</th>
<th>CM</th>
<th>CD</th>
<th>CDw</th>
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</thead>
<tbody>
<tr>
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<td>-0.0917</td>
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<td>Richardson</td>
<td>-</td>
<td>-</td>
<td>103.8</td>
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</tbody>
</table>
Test-Case 2 : RAE2822 optimization

Conclusions

• The test-case 2 has been successfully solved
• The final shape satisfies all constraints (lift, pitching moment and area) with almost no wave drag
• The use of the adjoint approach permits getting a fast optimization convergence, compatible with industrial constraints
• Optimization on too coarse mesh does not guarantee feasible and optimal solution on finer meshes. Optimization on too fine mesh is too time consuming. Cascading of optimization on successive fine meshes seems to be the most efficient approach.
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6. Conclusions
Test-Case 3: CRM wing optimization

Problem statement

- Optimization problem:
  - Min CD @ Mach=0.85, Re=5 \times 10^6
  - subject to constraint: CL \geq 0.5, CM \geq -0.17, Volume \geq Volume_{CRM}

- Aerodynamic model:
  - RANS, Spalart-Allmaras (frozen eddy-viscosity adjoint)
  - 2\textsuperscript{nd} order Roe Scheme
  - CFD mesh:
    - 55 blocks, 2M nodes

- Volume constraint:
  - use of GTS library

- Post-processing:
  - Far-field drag breakdown Onera ffd72 software

- Gradient optimizer:
  - MMFD (DOT)
Test-Case 3: CRM wing optimization

Parametrization

Camber + twist Parameterizations (type 1)

Profile shape + twist Parameterizations (type 2)

Refinement: 8 and 16 B-spline control points

Refinement: 1 to 5 Bezier control points
### Test-Case 3: CRM wing optimization

#### Summary of optimization runs (peut-on déduire le nombre de paramètres des colonnes 3 et 4 ?)

<table>
<thead>
<tr>
<th>Type</th>
<th>Chordwise parameters</th>
<th>Spanwise sections</th>
<th>Parameters</th>
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### Test-Case 3: CRM wing optimization

**Optimization results (1/4)**

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<td>191.74</td>
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</table>
Test-Case 3: CRM wing optimization

Optimization results (2/4)

Optimizations with type 1 - param

Chordwise refinement

Spanwise refinement
Test-Case 3: CRM wing optimization

Optimization results (3/4)

Best Optima for type 1 and 2 param.

Pressure distributions
Test-Case 3: CRM wing optimization

Optimization results (4/4)

Best Optima for type 1 and 2 param.

Geometrical characteristics
Test-Case 3: CRM wing optimization

Optimization results (5/5)

($\Gamma$ is the circulation of velocity about the profile)

Best Optima for type 1 and 2
Conclusions

• Several types of parameterization
  • Chordwise refinement: reduction of the wave and viscous pressure drag components
  • Spanwise refinement: improvement of the Oswald factor
  • $C_{Dvp}$ as objective: focus on the wave and viscous pressure components (possibly associated with a constraint on the induced drag component)

Prospects

• Further investigations in terms of parameterizations
• Can we reduce viscous pressure drag further? Impact of the optimization problem formulation
Concluding remarks

• 3 tests cases successfully treated using gradient optimizations and the adjoint capability of the elsA software.
• ADO workshop is a valuable initiative to exchange, validate and progress

• Recommendations for the next steps:
  • More test cases (geometries)? Maybe not …
  • Still work to be done regarding with proposed test cases:
    • Parameterization (efficient use of nested param (Désidéri))
    • Robust/efficient gradient optimization technique (constrained problems)
    • Impact of gradient accuracy (RANS adjoint, linearized turbulence model)
  • Global/hybrid optimization techniques?
  • Single vs multipoint / off-design characteristics optimization?
  • …
Aerodynamic Shape Optimizations of a Blended Wing Body Configuration for Several Wing Planforms

Prepared and presented by M. MEHEUT, A. ARNTZ and G. CARRIER
ONERA, Applied Aerodynamics Dept., Civil Aircraft
at the 30th AIAA Applied Aerodynamics Conference, June 2012

Also presented by J. PETER at the ANADE Workshop - Cambridge - September 24th 2014
NECST2/AVECA2 French project (funded by DGAC)

ONERA-Airbus technical cooperation based on the study of the AVECA flying wing configuration (< 600 passengers)

ONERA objectives

Define an optimization scenario at fixed wing planform using the adjoint approach with high fidelity tools (RANS equations) to maximize the aerodynamic performance in cruise conditions

Apply the optimization scenario on the several wing planforms selected by Airbus

Take into account low-speed constraints during the optimization process
Outline

1. Context
2. Description of the cruise optimization strategy
3. Definition of the cruise optimization scenario
4. Application of the optimization scenario on the reference wing planform
5. Application of the optimization scenario on several wing planforms
6. Cruise optimization with a low speed constraint
7. Conclusions and prospects
1. Context

2. Description of the cruise optimization strategy

3. Definition of the cruise optimization scenario

4. Application of the optimization scenario on the reference wing planform

5. Application of the optimization scenario on several wing planforms

6. Cruise optimization with a low speed constraint

7. Conclusions and prospects
Description of the cruise optimization strategy

Objective and constraints of the study

Starting point
Preliminary configuration designed by the Airbus future project offices

Objectives
Increase the lift-to-drag ratio or decrease the total drag at the design point in transonic conditions at a given $C_L$ (confidential flow conditions)

Constraints
Move downstream the centre of pressure (CP) to the estimated mean CG position
Respect geometrical constraints: cabin, cargo hold and landing gear volumes
Description of the cruise optimization strategy

Optimization chain using the adjoint approach

Multi-block C-type structured mesh (8 \(10^6\) nodes)

Coarsen mesh used during the optimization process (by a factor 2)

Optimization algorithm

CONMIN’s feasible directions method
Objective
Optimize the shape of several wing profiles in different sections on the inner and outer wings

Method
Definition of several control points in each section
Modifications of the geometry applied directly on the mesh (B-Spline curves)

Examples of parametrizations

13 parameters
- 6 Suction side
- 6 Pressure side
- Angle of attack

151 parameters
- 60 Suction side
- 60 Pressure side
- 10 Leading edge
- 10 Trailing edge
- 10 Twist
- Angle of attack
Description of the cruise optimization strategy
Validation of the adjoint method

RANS (SA) adjoint computations based on the “frozen $\mu_t$ hypothesis”

Resulting errors on the sensitivities of the objective and constraint functions i.e. on the gradient direction defined by the optimizer

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
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<td>-1.1%</td>
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<td>5.2%</td>
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<tr>
<td>$C_{Dff}$</td>
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<td>9.2%</td>
</tr>
</tbody>
</table>

Differences between the gradients of the adjoint method and a centered finite difference approach normalized by the maximum gradient value

Sufficient results
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1. Context
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4. Application of the optimization scenario on the reference wing planform
5. Application of the optimization scenario on several wing planforms
6. Cruise optimization with a low speed constraint
7. Conclusions and prospects
Definition of the cruise optimization scenario

Optimization problem

Objective: Maximize the lift-to-drag ratio

Constraints: location of the centre of pressure, geometric volumes and lift coefficient

Parametrizations

62 parameters
- 30 Suction side
- 10 Pressure side
- 5 Leading edge
- 5 Trailing edge
- 11 Twist
- Angle of attack

151 parameters
- 60 Suction side
- 60 Pressure side
- 10 Leading edge
- 10 Trailing edge
- 10 Twist
- Angle of attack
Definition of the cruise optimization scenario

**Results**

At the design point both optimized configurations have the same lift-to-drag ratio.

To reduce the 3 drag components:

2 steps

**Aerodynamic performance**

- **62 parameters**
  - Improvement of the wave and viscous drag components

**Spanwise drag distributions**

- **151 parameters**
  - Improvement of the wave and induced drag components

Step 1: Minimization of the far-field drag with 62 parameters (3 constraints)

Step 2: Maximization of the lift-to-drag ratio at the design point with 151 parameters (with 3 constraints)
Outline

1. Context
2. Description of the cruise optimization strategy
3. Definition of the cruise optimization scenario
4. Application of the optimization scenario on the reference wing planform
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Application of the optimization scenario
Optimization history

Step 1 from the initial configuration
DEF=design parameters  xCP=abs. center of pressure forces
(null pitching moment) needed for stability constraints

Step 2 from step 1
DEF=design parameters xCP=abs. center of pressure forces(null
pitching moment) needed for stability constraints

270 evaluations
26 gradients
1 200 hours (1 processor)*

64 evaluations
12 gradients
350 hours (1 processor)*

*On NEC-SX8
Application of the optimization scenario

Results

Aerodynamic performance

Spanwise drag distributions
(/dy = y-slice contribution, not derivative)

Very strong improvement of the lift-to-drag ratio (2 counts)

Reduction of the 3 drag components: viscous (3.7%), wave (90.0%), induced (5.0%)
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Description of the different trades (changing shape and weight changes $C_z$ at same high/Mach number and also pitching moment $C_M$)

- **Trade 1**: 10% increase of the inner wing chord
- **Trade 2**: 5% decrease of the inner wing chord
- **Trade 3**: 5% decrease of the inner wing thickness
- **Trade 5**: 5% increase of the inner wing sweep angle
- **Trade 10**: 5% decrease of the inner wing span, 5% increase of the inner wing chord and 5% increase of the total wing span
- **Trade 12**: fixed inner wing and 10% increase of the total wing span

Redefinition of the aerodynamic ($C_L$ and $C_M$) and geometric (cabin, cargo-hold and landing gear volumes) constraints for each trade
Application of the optimization scenario

Influence of the inner wing chord – LoD

Strong influence of the re-optimisation for both trades 1 and 2

Increase of the lift-to-drag ratio at the design point for the trade 1 (compared to the trade 0)

Decrease of the lift-to-drag ratio at the design point for the trade 2 (compared to the trade 0)

Configurations without reoptimization:
wing planform modification of the optimized configuration for the trade 0
(LoD count = 1 for the ratio of dimensional values)

Polar curves = varying AoA
Application of the optimization scenario

Influence of inner wing chord – Drag components

(\textit{même question. Une variation de composante de traînée en }x\textit{ est obtenue en faisant varier AoA ?})

- Wave drag
- Viscous drag
- Induced drag

Strong influence of the re-optimisation on the wave drag at the design point

Very small of the re-optimisation on the induced drag

Important influence of the re-optimisation on the viscous drag at the design point mainly for the trade 1
Application of the optimization scenario
Influence of the inner wing thickness and sweep angle - LoD

Strong influence of the re-optimisation for the trade 5

No influence of the re-optimisation for the trade 3

Increase of the lift-to-drag ratio at the design point for both trade (compared to the trade 0)
Application of the optimization scenario

Influence of the inner wing thickness and sweep angle - LoD

- **Wave drag**: Strong influence of the re-optimisation on the wave drag for high angles of attack for the trade 5.

- **Viscous drag**: Important influence of the re-optimisation on the viscous drag at the design point only for the trade 5.

- **Induced drag**: No influence of the re-optimisation on the induced drag.
Application of the optimization scenario
Influence of the wingspan – LoD

For the trade 10, reduction of the aerodynamic performance with the reoptimization (strong violation of the geometric constraint for the non-optimized configuration)

For the trade 12, improvement of the aerodynamic performance with the reoptimization

For both trades, increase of the lift-to-drag ratio (compared to the trade 0)
Application of the optimization scenario
Influence of the wing span – Drag components

Wave drag
Viscous drag
Induced drag

Strong influence of the re-optimisation on the wave drag notably for both trades

Important influence of the re-optimisation on the viscous drag

No influence of the re-optimisation on the induced drag
Application of the optimization scenario

Summary – LoD

Influence of the re-optimization at the design point on the LoD

<table>
<thead>
<tr>
<th>Trade</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>5</th>
<th>10</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without re-optimization</td>
<td>0.02</td>
<td>-0.25</td>
<td>0.44</td>
<td>0.05</td>
<td>0.54</td>
<td>0.64</td>
</tr>
<tr>
<td>With re-optimization</td>
<td>0.50</td>
<td>-0.07</td>
<td>0.57</td>
<td>0.23</td>
<td>0.32</td>
<td>1.08</td>
</tr>
</tbody>
</table>

Ranking of the configurations at their respective design point

**Without re-optimization**: 1.TRADE 12, 2.TRADE 10, 3.TRADE 3, 4.TRADE 0, 5.TRADE 5, 6.TRADE 1, 7.TRADE 2

**With re-optimization**: 1.TRADE 12, 2.TRADE 3, 3.TRADE 1, 4.TRADE 10, 5.TRADE 5, 6.TRADE 0, 7.TRADE 2
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Cruise optimization with a low speed constraint

**Objective and constraints**

**Objective**
Design a viable configuration in cruise conditions but also in low-speed conditions
(also confidential flow conditions)

**Constraints**
Cabin, cargo hold and landing gear volumes
Cruise
Lift coefficient
Location of the centre of pressure (CP)
Low-speed
Take-off rotation criterion
(minimum nose-up pitching moment $C_{Mo}^*$ at zero lift)

**Starting point of the optimization**
Cruise optimized configuration (trade 0)
Cruise optimization with a low speed constraint

Modified optimization chain using the adjoint approach

Global shape parametrization

151 parameters
Cruise optimization with a low speed constraint

Results

Aerodynamic performance

Identical aerodynamic performance for both configurations at the design point

For higher lift coefficients, small decrease of the lift-to-drag ratio

Spanwise drag distributions
Cruise optimization with a low speed constraint

Low speed constraint and shape modifications

Low-speed constraint

Pressure side

Suction side

Decrease of the camber

Increase of the camber

Shape modifications
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Conclusions and prospects

Conclusions

• Definition of an optimization scenario for the AVECA configuration in 2 steps using the adjoint approach
• Application of the scenario on the reference wing planform
• Wing planform parameter analysis with a systematic reoptimization (chord, thickness, sweep, wingspan)
• Integration of a low-speed constraint during the optimization process (take-off rotational criterion)

Prospects

• Design of vertical surfaces (winglet, tail plane)
• Taking into account additional low-speed and flight handling quality constraints during the cruise optimization process
• Integration of engines