An Adjoint-based Optimization Method for Helicopter Backdoor Geometry

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Overview

- Motivation
- Description of the optimization approach

- Surface parameterization and deformation techniques
  - Method 1: NURBS surface parameterization + RBF mesh deformation
  - Method 2: Mesh deformation via FFD + RBF deformation chain

- Optimization results for a helicopter backdoor geometry

- Summary and Outlook
Motivation

- Typical breakdown of parasite drag components of a representative helicopter

After Prouty (1986)
Motivation

- European research project: Clean Sky - Green Rotorcraft
  - reach higher efficiency by the means of drag reduction

- Fuselage drag reduction of transport helicopters
  - backdoor area is usually the biggest drag contributing area
    - regions of flow separation, formation of two trailing vortices
  - global geometry parameters usually limited by mission requirements
    - cross-section size, upsweep angle, contraction ratio
  - local shape optimization

- Backdoor geometry in general 3D and diff. for param.
  - a large number of design variables
  - gradient-based optimization
    - efficient gradient evaluation using the adjoint approach
Overview of the Optimization Chain

- **CFD Solver**: unstructured RANS solver TAU
- **Adjoint Solver**: solver for the discrete adjoint equation
- **Gradient calculation**: conjugate gradient
- **Minimum search**: line search method

$X$: geometry variables

$D$: design variables

$I$: object function ($C_D$)

- Initial Geometry
- CFD Solver
- Adjoint Solver
- Gradient Calculation
- Optimized Geometry
- Minimum found?
- Design Cycle
- Intermediate Geometry
- Geometry Deformation
- CFD Solver
- 3 Points Pattern?
- 1D line search

Python Skript
Computational setup of the CFD simulation - mesh parameters

- GRC2 Geometry: a modified NH90 geometry
- Grid generator: Centaur
- First cell height: 0.005mm
- Far field radius: $20 \times L_{\text{fuselage}} = 80m$
- Total grid points: 5.73 mio.

- mostly quadrilateral surface elements
- structured hexahedral elements on backdoor
- mesh deformation applied only locally (red mesh)
Computational setup of the CFD simulation
- simulation parameters

**CFD Simulations:**
- DLR TAU Code
  - compressible unstructured RANS solver
- spatial discretization:
  - 2nd order central scheme with artificial dissipation (Jameson)
- time integration:
  - implicit LUSGS scheme
- turbulence model:
  - Spalart-Allmaras model

**Cruise flight condition at Sea Level ISA:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free stream air speed</td>
<td>$U_\infty$</td>
<td>m/s</td>
<td>70</td>
</tr>
<tr>
<td>Pressure</td>
<td>$P_\infty$</td>
<td>Pa</td>
<td>101325</td>
</tr>
<tr>
<td>Density</td>
<td>$\rho_\infty$</td>
<td>kg/m³</td>
<td>1.225</td>
</tr>
<tr>
<td>Temperature</td>
<td>$T_\infty$</td>
<td>K</td>
<td>288</td>
</tr>
<tr>
<td>Angle of attack</td>
<td>$\alpha$</td>
<td>Deg</td>
<td>-2</td>
</tr>
<tr>
<td>Sideslip angle</td>
<td>$\beta$</td>
<td>Deg</td>
<td>0</td>
</tr>
<tr>
<td>Free stream Reynolds number</td>
<td>$Re$</td>
<td>1/m</td>
<td>$4.79 \times 10^6$</td>
</tr>
<tr>
<td>Free stream Mach number</td>
<td>$Ma$</td>
<td>-</td>
<td>0.206</td>
</tr>
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</table>
Basic formulation of the adjoint method

- **Cost function:** $I = I(W, X(D))$  
  $X(D)$: computational mesh,  
  $W(D)$: vector of flow variables

- **Gradient of the cost function:**
  $$rac{dI}{dD} = \frac{\partial I}{\partial X} \frac{dX}{dD} + \frac{\partial I}{\partial W} \frac{dW}{dD}$$  
  Using the brute force of Finite Difference:  
  $N$ flow solutions for $N$ design variables

- **Lagrangian function:**  
  $L = I + \Lambda^T R$  
  $R(W, X(D))$: flow residual,  
  $\Lambda$: Lagrangian multiplier

  $$
  \frac{dL}{dD} = \left[ \frac{\partial I}{\partial X} + \frac{\Lambda^T \partial R}{\partial D} \right] \frac{dX}{dD} + \left[ \frac{\partial I}{\partial W} + \Lambda^T \frac{\partial R}{\partial W} \right] \frac{dW}{dD}
  $$

- **Adjoint equation:**
  $$
  \left[ \frac{\partial R}{\partial W} \right]^T \Lambda = - \left[ \frac{\partial I}{\partial W} \right]^T
  $$

  $$
  \frac{dI}{dD} = \frac{dL}{dD} = \left[ \frac{\partial I}{\partial X} + \Lambda^T \frac{\partial R}{\partial X} \right] \frac{dX}{dD}
  $$
  The additional effort of the adjoint method:  
  one solution of the adjoint equation $\approx$ one flow solution
Defo Method 1: Surface parameterization using NURBS

Original geometry

NURBS Curve
\[ C(u) = \frac{\sum_{j=0}^{n} N_{i,p}(u) w_j d_i}{\sum_{j=0}^{n} N_{i,p}(u) w_j} \quad 0 \leq u \leq 1 \]

NURBS Surface
\[ S(u,v) = \frac{\sum_{i=0}^{m} \sum_{j=0}^{n} N_{i,p}(u) N_{j,q}(v) w_{i,j} d_{i,j}}{\sum_{i=0}^{m} \sum_{j=0}^{n} N_{i,p}(u) N_{j,q}(v) w_{i,j}} \quad 0 \leq u, v \leq 1 \]

An approximated NURBS surface with control points is generated

Design variables: x and z of 48 control points

96 design variables

Control points on boundaries unchanged

(DA: J.-H. Wendisch)
Defo Method 1: Surface parameterization using NURBS
- surface deformation by deflecting the control points \((D)\)

Control points on the boundary are kept unchanged

- Original geometry
- Deformed geometry
- Red cube: control points of the deformed geometry
- Orange sphere: control points of the undeformed geometry
Defo Method 1: Volume mesh deformation using RBF
- application to the helicopter backdoor

Advantage of RBF mesh deformation:
boundary layer resolution of the mesh can be kept nearly unchanged

This feature is very important for the drag evaluation
Results of the optimization study
- history plot of the cost function $C_D$

Drag coeff. of the orig. geometry:
$C_{D,\text{orig}} \cdot S = 5.169 \times 10^{-2} \ 1/m$

Drag coeff. of the opt. geometry:
$C_{D,\text{opt}} \cdot S = 5.058 \times 10^{-2} \ 1/m$

Total drag reduction: $\Delta C_D = -2.15\%$

Lift coefficient increased slightly

On 32 AMD Opteron Processor 2384:
- One flow calculation (restart): 5h
- One adjoint calculation: 25~30h

Crosscheck with Wilcox k-$\omega$ model:

<table>
<thead>
<tr>
<th>$C_D$</th>
<th>Spalart-Allmaras</th>
<th>Wilcox k-$\omega$</th>
<th>Diff.</th>
</tr>
</thead>
<tbody>
<tr>
<td>orig.</td>
<td>$5.169 \times 10^{-2}$</td>
<td>$5.455 \times 10^{-2}$</td>
<td>+ 5.53%</td>
</tr>
<tr>
<td>opt.</td>
<td>$5.058 \times 10^{-2}$</td>
<td>$5.356 \times 10^{-2}$</td>
<td>+ 5.89%</td>
</tr>
<tr>
<td>Diff.</td>
<td>- 2.15%</td>
<td>- 1.81%</td>
<td></td>
</tr>
</tbody>
</table>
Results of the optimization study
- optimized backdoor geometry

Blue: original geometry
Red: optimized geometry

Magnitude of the mesh node displacements
Results of the optimization study
- skin friction coefficients and surface stream lines

Original geometry

Optimized geometry
Results of the optimization study
- local drag coefficients of the neighboring components

Drag coeff. of the original backdoor:
\[ C_{D_{\text{orig}} \cdot S} = 7.176 \times 10^{-3} \, 1/m \]

Drag coeff. of the optimized backdoor:
\[ C_{D_{\text{opt}} \cdot S} = 6.030 \times 10^{-3} \, 1/m \]

Local drag reduction on backdoor:
\[ \Delta C_{D_{Bd}} = -15.97\% \]
Defo Method 2: Mesh deformation via a FFD & RBF chain
- basic principle of Free Form Deformation (FFD)

- Flexibility: number of design variables can be chosen by user (with compromise in accuracy)
- Robustness: very robust especially on Euler meshes
- Crashes during volume mesh deformation, especially for N-S meshes  ▸ broken optimization chain

(taken from A. Ronzheimer 2005)
Defo Method 2: Mesh deformation via a FFD & RBF chain
- definition of the FFD box (shematic)

- Idea: combine the advantages of FFD and RBF
- Generate surface point pairs in local surface normal direction with CATIA
- Define FFD-Box, boundary points will not be moved
Defo Method 2: Mesh deformation via a FFD & RBF chain
- steps of mesh deformation

- Input: FFD-box, coarse mesh for back door
- Displacement of the FFD box point, perform FFD for a coarse dummy mesh
- Calculate displacement of the surface points of the dummy mesh
- Write out scattered data points to be used for the RBF deformation of the final CFD mesh
- Use the scattered data points for the deformation of the final mesh
Defo Method 2: Mesh deformation via a FFD & RBF chain
- example of a deformed mesh (schematic representation)

- Displacement of FFD points according to given optimizer directives
- deformed surface of the CFD mesh
- Formation of strake-like geometry
Defo Method 2: Mesh deformation via a FFD & RBF chain
- Implementation of geometrical constraints

- Another advantage: geometrical constraints can be relatively easily introduced

- Till now: Constraints are implemented by manipulating the RBF scattered data (“cheating” the optimizer)

- Better: treat them as constraints of the optimization problem (e.g., sequential quadratic programming)
Results of the optimization study on GRC2 geometry
- comparison of the history plot of the cost function $C_D$

- Deformation Method 1: 96 design variables
- Deformation Method 2: 16 design variables
- Deformation Method 2 has been successfully applied to a redesigned EC-135 Geometry
- Application to the GRC2 geometry and detailed analysis of results is still on-going
Summary

- A adjoint-based optimization chain has been applied for a helicopter backdoor geometry
- Design variables are the NURBS control points of the backdoor geometry, or the normal displacement of the defined FFD control box
- Applying local shape optimization, a total drag reduction of ca. -2 ~ -3.5 % on the GRC2 geometry could be achieved

Outlook

- Employing more realistic geometrical or structural constraints
- Check for more parameterization methods for the purpose of reducing the total number of design variables
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  Using the brute force of Finite Difference: \( N \) flow solutions for \( N \) design variables

- **Lagrangian function:** \( L = I + \Lambda^T R \) \( R(W, X(D)) \): flow residual, \( \Lambda \): Lagrangian multiplier

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  \]

  \[
  \frac{dL}{dD} = \left[ \frac{\partial I}{\partial X} + \Lambda^T \frac{\partial R}{\partial D} \right] \frac{dX}{dD} + \left[ \frac{\partial I}{\partial W} + \Lambda^T \frac{\partial R}{\partial W} \right] \frac{dW}{dD}
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- **Adjoint equation:**
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  \]
  The additional effort of the adjoint method:
  one solution of the adjoint equation \( \approx \) one flow solution
Defo Method 1: Surface parameterization using NURBS
- Adjoint-based gradient calculation

Flow solution (skin friction coeff. and surface stream lines)

Adjoint equation

Sensitivity evaluation

Gradient of the cost function w.r.t. the design variables
Defo Method 1: Volume mesh deformation using RBF
- basic principles

Classical Volume spline with coefficients $\alpha_i$, $\beta_i$ with an additional blending function dependent on the wall distance

$$f(wd) = \Delta x(y, z) = f(wd)(\alpha_1 + \alpha_2 x + \alpha_3 y + \alpha_4 z + \sum_{i=1}^{N} \beta_i \sqrt{(x-x_i)^2 + (y-y_i)^2 + (z-z_i)^2})$$
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Results of the optimization study
- pattern of pressure coefficients ($C_p > 0$)

- the areas with pressure value $C_p > 0$ produce force components
  - in the flight direction (pressure drag reduction)
  - in the upward direction (lift increase)