Adjoint-Based Topology and Shape Optimization for Car Development

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The Volkswagen Group

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<tr>
<th>Volkswagen</th>
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**Volkswagen Corporate Research:** ~600 people in Wolfsburg (Germany) + satellites in Tokyo, Shanghai and Belmont
Adjoint-Based Optimization for Cars: Overview

- Continuous Adjoint Method
- Flow Control
- Cooling Optimization
- Vehicle Shape Optimization
- Shape Optimization of Ducted Flows
- Aeroacoustic Optimization
- Topology Optimization
Acknowledgements

• Prof. Giannakoglou’s team at the National Technical University of Athens

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The Adjoint Method: Computation of Sensitivity Maps

**Surface Sensitivities** = $\frac{\partial J}{\partial \beta}$
- **red**: push away from the fluid
- **blue**: push towards the fluid

**Volume Sensitivities** = $\frac{\partial J}{\partial \alpha}$
- **red**: important areas
- **blue**: counterproductive areas

- **Massflow**
- **Drag**
- **Pressure drop**
- **Uniformity**
### The Adjoint Method: Computational Process

1. **CFD computation:** $v$, p (“primal field“)

   $$(v \cdot \nabla)v = -\nabla p + \nabla \cdot (\nu \nabla v) - \alpha v$$
   $$\nabla \cdot v = 0$$

2. **Adjoint CFD computation:** $u$, q (“dual field“)

   $$- (\nabla u) v - (v \cdot \nabla) u = -\nabla q + \nabla \cdot (\nu \nabla u) - \alpha u$$
   $$\nabla \cdot u = 0$$

3. **Computation of sensitivities:**

   - **Volume sensitivities:**\[ \frac{\partial J}{\partial \alpha} \sim v \cdot u \]
   - **Surface sensitivities:**\[ \frac{\partial J}{\partial \beta} \sim \frac{\partial v}{\partial n} \cdot \frac{\partial u}{\partial n} \]
Implementation of an Adjoint Solver for Automotive Applications

- Platform: Open source code OpenFOAM® chosen in 2006

```c
solve ( fvm::ddt(rho, U) + fvm::div(phi, U) - fvm::laplacian(mu, U)
  == - fvc::grad(p) );
```

- Topology optimization [VW, AIAA 2007]
- Shape sensitivities [VW, IJNMF 2008]
- Low-Re Adjoint turbulence [NTUA + VW, C&F 2009]
- Adjoint wall functions [NTUA + VW, JCP 2010, ECCOMAS 2014]
- Packaging and further industrialization by Engys [since 2011]
- Uptake and improvements by Helgason, Hinterberger, Jakubek, Lincke, Towara, ...

→ Versatile continuous adjoint solver “adjointFoam“ for incompressible steady-state RANS
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Topology Optimization

- Well-developed tool in structure mechanics, wide-spread industrial use

Example: Optimal car body topology [Conic, VW]

- Transfer to fluid dynamics: Borrvall and Petersson [2003]
Topology Optimization for Fluid Dynamics

- Starting point: **Entire installation space**
  - Flow solution
  - Identification of “counter-productive” cells via a local criterion \(v \cdot u\)
  - Punishment of counter-productive cells with porosity

- Result: Optimal topology
Topology Optimization for Fluid Dynamics

- Starting point: ** Entire installation space**
  - Flow solution
  - Identification of “counter-productive“ cells via a **local criterion** \((v\cdot u)\)
  - Punishment of counter-productive cells with porosity

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Topology Optimization for Fluid Dynamics

• Starting point: **Entire installation space**
  - Flow solution
  - Identification of “counter-productive” cells via a local criterion ($v \cdot u$)
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• Result: Optimal topology
Topology Optimization for Fluid Dynamics

• Starting point: Entire installation space
  – Flow solution
  – Identification of “counter-productive” cells via a local criterion \((v \cdot u)\)
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• Result: Optimal topology
Topo Example 1: From Packaging Space to the Optimal Port

Packaging space definition

Drafting with adjointFoam + manual CAD iterations

Fine-tuning with adjointFoam

Final (hand-made) CAD geometry

[F. Kunze and R. Niederlein]
Topo Example 2: Multi-Objective Intake Port Optimization

\[ \Delta p: -1.4\% \]
\[ \omega: +25\% \]
\[ +35\% \]
\[ +257\% \]
\[ +123\% \]
\[ +544\% \]
CFD Topology Optimization: Application Spectrum
Shape Optimization for Ducted Flows: Exhaust Port Example

Original

Optimized
+5% mass flow

Mass flow sensitivities

[F. Kunze and R. Niederlein]
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Shape Optimization in External Aerodynamics: Example 1

- Volkswagen XL1
- \( v = 33 \text{m/s} \)
- RANS with Spalart-Allmaras
- low-Reynolds mesh (\( y^+ \sim 1 \))
- half-model
Volkswagen XL1: Sensitivities (1)

**red**: inwards for smaller drag
**blue**: outwards
Volkswagen XL1: Sensitivities (2)

**red:** inwards for smaller drag  
**blue:** outwards
One-Shot Optimization of the Rear Spoiler

- 5 free-form-deformation control points defined to control rear edge
- Variation in the z-direction only → 5 design variables
- Objective function: Drag
Optimization Results

- >2% drag reduction, 30% lift improvement
- Deformation in z-direction < 20mm
- Overall cost: <5 EFS
Shape Optimization in External Aerodynamics: Example 2

- External mirror shape optimization w.r.t. total vehicle drag
- Sensitivities by adjointFoam, morphing with Carat (TU Munich)

- Conservation of feature lines is an essential ingredient for external aero optimization
Productive Aerodynamics Computations: DES instead of RANS
Approximate DES-Based Sensitivities

1. Basis: Time-averaged primal DES, compute drag and lift coefficients
2. Take time-averaged primal velocity and solve for a RANS-$\nu_t$
3. Run adjoint RANS with averaged primal velocity and $\nu_t$

- Finite differences: far off, *qualitative* agreement only
RANS vs. DES: Case Study Audi A7
RANS vs. DES: Drag Sensitivities Audi A7
RANS vs. DES: Drag Sensitivities Audi A7

Productive effect of boat-tailing verified in wind tunnel tests
Drag Sensitivity Maps Based on DES: Further Examples

- **red:** inwards for smaller drag
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Case Study Volkswagen XL1: Drag Sensitivities

Sensitivity Map of $\frac{dF_x}{dv_n}$, with $v_n$: blowing/suction velocity

**blue:** blowing favourable

**red:** suction favourable
Wind Tunnel Measurements on a 1:4 Model

- Placement of blowing jets on the rear underbody
- Cooperation with TU Braunschweig

Force measurements and oil-film flow visualization

PIV measurements of the wake structure
PIV Measurements behind the Car

- Much weaker longitudinal vortices
- Significant reduction on rear lift: 0.10 → 0.08
- Measurable effect on drag (<1%), but still too small to be economic
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Continuous Adjoint Method
Main Motivation: Cylinder Head Cooling

Solid part of the cylinder head
Main Motivation: Cylinder Head Cooling

Fluid volume ("water jacket")
Main Motivation: Cylinder Head Cooling

Streamlines
Extension of the Adjoint Solver towards Conjugate Heat Transfer

- Development and validation of an adjoint conjugate heat transfer code (NTU Athens in cooperation with Volkswagen Research)
- Objective function: average $T^n$ in the solid domain
- Design variables: node displacements along the fluid/solid interface
- Test case: square channel

[from H. Narten, VW EA]
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<thead>
<tr>
<th>Change</th>
<th>absolute</th>
<th>relative</th>
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<tr>
<td>Heat Flux</td>
<td>+ 253 W</td>
<td>+ 47 %</td>
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<tr>
<td>Pressure Drop</td>
<td>+ 7 Pa</td>
<td>+ 13 %</td>
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[from H. Narten, VW EA]
Check 1: Physics or Numerical Noise?

- 10 times higher resolution along the interface
- Result: Deviation of heat flux < 0.5%

[Diagrams showing comparison between Original and Fine Mesh results, with [from H. Narten, VW EA] information]
Check 2: Comparison with Sinusoidal Wave Pattern

- Wavelength taken from FFT of optimized interface
- Heat flux significantly lower for sinusoidal waves (-20%)

[from H. Narten, VW EA]
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Surrogate cost functions:

- \( n u_t \) inside a volume adjacent to the side window
- \((\text{wall shear stress})^2\) integrated over the side window

More adequate cost function:

- \( J = (p(t) - p_{\text{avg}})^2 \)

Time-varying adjoint source term:

- \( \text{div } u = p(t) - p_{\text{avg}} \)
Towards Unsteady Adjoint: DES Drag Sensitivities

[From N. Magoulas, VW Research]
Summary

Vehicle Shape Optimization

Flow Control

Continuous Adjoint Method

Shape Optimization of Ducted Flows

Cooling Optimization

Aeroacoustic Optimization

Topology Optimization