The Adjoint Method Hits the Road: Applications in Car Aerodynamics

Dr. Carsten Othmer, Volkswagen AG, Corporate Research, Wolfsburg, Germany
Adjoint-Based Optimization for Cars: Overview

- **Vehicle Shape Optimization**
- **Flow Control**
- **Cooling Optimization**
- **Shape Optimization of Ducted Flows**
- **Aeroacoustic Optimization**
- **Topology Optimization**

**Continuous Adjoint Method**
Acknowledgements

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

• Eugene De Villiers and Thomas Schumacher from Engys, London

• E. Stavropoulou, M. Hojjat and Prof. Bletzinger from TU Munich

• The Adjoint team at Volkswagen: S. Baumbach, K. Brandes, M. Gregersen, F. Kunze, N. Magoulas, J. Müller, H. Narten, D. Schräder and other supportive colleagues
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: \( \mathbf{v}, p \) ("primal field")

\[
\begin{align*}
(\mathbf{v} \cdot \nabla) \mathbf{v} &= -\nabla p + \nabla \cdot (\nu \nabla \mathbf{v}) - \alpha \mathbf{v} \\
\nabla \cdot \mathbf{v} &= 0
\end{align*}
\]

2. Adjoint CFD computation: \( \mathbf{u}, q \) ("dual field")

\[
\begin{align*}
-(\nabla \mathbf{u}) \mathbf{v} - (\mathbf{v} \cdot \nabla) \mathbf{u} &= -\nabla q + \nabla \cdot (\nu \nabla \mathbf{u}) - \alpha \mathbf{u} \\
\nabla \cdot \mathbf{u} &= 0
\end{align*}
\]

3. Computation of sensitivities:

- Volume sensitivities: \( \frac{\partial J}{\partial \alpha} \sim \mathbf{v} \cdot \mathbf{u} \)

- Surface sensitivities: \( \frac{\partial J}{\partial \beta} \sim \frac{\partial \mathbf{v}}{\partial n} \cdot \frac{\partial \mathbf{u}}{\partial n} \)
Implementation of an Adjoint Solver for Automotive Applications

- Platform: Open source code OpenFOAM® chosen in 2006

```cpp
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
Adjoint-Based Optimization for Cars: Overview

Continuous Adjoint Method

Flow Control

Vehicle Shape Optimization

Cooling Optimization

Shape Optimization of Ducted Flows

Aeroacoustic Optimization

Topology Optimization
Topology Optimization

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

Example: Optimal car body topology [Conic, VW]

- Transfer to fluid dynamics: Klimetzek [Daimler, 2003], 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** $(\mathbf{v} \cdot \mathbf{u})$
  - 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

• Result: Optimal topology

![Evolution of the duct shape](image)
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
Topo Example 1: From Packaging Space to the Optimal Port

Packaging space definition

Drafting with adjointFoam

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

[F. Kunze, U. Giffhorn]

[M. Tomecki]

[C. Ehlers, K. Arntz]

[U. Giffhorn]

[N. Peller]

[U. Giffhorn]

[R. Niederlein]

[P. Unterlechner]

[M. Towara]
Shape Optimization for Ducted Flows: Exhaust Port Example

Original

Optimized +5% mass flow

Mass flow sensitivities

[F. Kunze and R. Niederlein]
Adjoint-Based Optimization for Cars: Overview
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 $\rightarrow$ 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

[SAE 2009-01-0333]
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
*blue:* outwards
Adjoint-Based Optimization for Cars: Overview

- Flow Control
- Cooling Optimization
- Vehicle Shape Optimization
- Shape Optimization of Ducted Flows
- Aeroacoustic Optimization
- Topology Optimization

Continuous Adjoint Method
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
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
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]
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

<table>
<thead>
<tr>
<th>Change</th>
<th>absolute</th>
<th>relative</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Flux</td>
<td>+ 253 W</td>
<td>+ 47 %</td>
</tr>
<tr>
<td>Pressure Drop</td>
<td>+ 7 Pa</td>
<td>+ 13 %</td>
</tr>
</tbody>
</table>

[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%

[from H. Narten, VW EA]
Check 2: Comparison with Sinusoidal Wave Pattern

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

**RANS**

Surrogate cost functions:

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

**DES [from M. Hartmann, VW Research]**

More adequate cost function:

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

Time-varying adjoint source term:

- \( \text{div} \; u = p(t) - p_{avg} \)
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