Multi-objective adjoint optimization of flow in duct and pipe networks

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Engys

• UK, Germany and Italy

• Open Source software for industrial application
  ▪ CFD, FEM, Optimisation
  ▪ OPENFOAM®, Code_Aster, Dakota

• Software services
  ▪ Outsourcing/Consultancy
  ▪ Training
  ▪ Support
  ▪ Development

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Optimisation

• What is Design Optimisation?
  ▪ Design for increased efficiency
  ▪ Better performance, lower operating cost, robustness, increased reliability, etc.

• Why optimise?
  ▪ Reduced process and product cost
  ▪ Better product
  ▪ Regulatory pressure

• Virtually anything can be optimised given a favourable cost-benefit ratio

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• How to optimise geometry
  - Experience (cognitive model)
  - Analytical (limited class of problems)
  - Reduced order models (response surface, POD)
  - Evolutionary (genetic, neural)
  - Finite difference (gradient methods)
  - Adjoint
  - Hybrid
Adjoint Methods | Background

• Conceptually, what is the adjoint method?

“Method for the evaluation of the derivative of a function \( I(s) \) with respect to parameters \( s \) in situations where \( I \) depends on \( s \) indirectly, via an intermediate variable \( w(s) \), which is computationally expensive to evaluate.” - René Schneider, 2006

- In figurative terms, it's like turning the governing equations inside-out to see how local changes will affect global objectives.
- In the context of CFD, it can tell you how changes to any cells porosity or a surface vertex’s position \( (s) \) will affect an objective function like pressure drop \( (I) \), without having to calculate the effect of such changes \( (in s) \) on the velocity and pressure \( (w) \).
- There is a lot of mathematics.
Adjoint Methods | Background

• Derived using augmented cost function and the method of Lagrange multipliers:

Adjoint variables (unknown)

Objective: \( J(V, p, \alpha) \)

Navier-Stokes: \( R(V, p, \alpha) \)

Augmented cost function: \( L = J + \int_{\Omega} (U, q) R d\Omega \)

For \( L \) to be an optimum, the following must be true:

\[
R(V, p) = 0, \frac{\partial L}{\partial (V, p)} = 0, \frac{\partial L}{\partial \alpha} = 0
\]

Adjoint equations

Sensitivity gradients
Adjoint Methods | Background

- Continuous adjoint equations:
  \[
  \frac{\partial L}{\partial (\mathbf{V}, p)} = 0 \rightarrow \left\{ \begin{align*}
  \nabla \cdot \mathbf{U} &= 0 \\
  -\left[ \nabla \mathbf{U} + (\nabla \mathbf{U})^T \right] \cdot \mathbf{V} + \nabla \cdot \left( q\mathbf{I} - \nu_e \left[ \nabla \mathbf{U} + (\nabla \mathbf{U})^T \right] \right) &= 0
  \end{align*} \right\}
  \]

- Adjoint sensitivity:
  \[
  \frac{\partial L}{\partial \alpha} = \mathbf{U} \cdot \mathbf{V} d\Omega
  \]
  
  - finds the source of a specific anomaly
  - does NOT model physical quantities
  - models the sensitivity of a property to these quantities

Upstream convection of adjoint rate of strain
Adjoint Methods | Implementation

- Basic equations fixed
  - Only boundary conditions and source terms change for different objectives
- Can be easily implemented in OPENFOAM®
  - see Othmer, De Villiers & Weller; AIAA-2007-3947
- Solution time independent of number of parameters to be optimised
  - Main benefit over conventional optimisation techniques
Adjoint Methods | Implementation

- OPENFOAM® native solver
  - Developed in cooperation between Engys DE and Dr. Carsten Othmer of VW Research
  - Supported by Uwe Giffhorn & Wolfgang Py (VW Engine Dev.)

- Topology optimisation
  - Parameter independent gradient based method
  - Fully integrated multi-objective
    - Minimze pressure drop
    - Maximize uniformity
    - Minimize forces
    - Maximize swirl

- Compressible/incompressible support

- Output: approximate design

- Cost $\rightarrow$ ~20 times single RANS simulation
Right-Angled Duct

- Basic 2D case to show the fundamental properties
- Pressure drop -6%, Uniformity +7%
Right-angled Duct

- Snapshot after 200 iterations

Low outlet velocity encourages adjoint outflow

Above average outlet velocity generates uniformity adjoint inflow
Duct Network

• 2D duct network
• Objectives:
  ▪ Minimise pressure drop
  ▪ Target mean velocity at all outlets (1 m/s)
• Steady incompressible RANS
• Pressure drop -31%
• Uniformity +50%
Duct Network

- 2D duct network – pressure loss: uniformity – 1:100

ΔP = 15.1 Pa  γ = 0.63

ΔP = 10.5 Pa  γ = 0.95
Air-intake

• Automotive air intake system with particulate filter and water separation components

• Objectives
  ▪ Reduce losses
  ▪ Improve outlet uniformity to increase filter utilisation
  ▪ Produce pressure-loss, uniformity trade-off curve

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## Objectives

<table>
<thead>
<tr>
<th>CASE</th>
<th>Pressure Drop [Pa]</th>
<th>( \Delta p ) %</th>
<th>Outlet Uniformity</th>
<th>( \Delta \gamma ) %</th>
</tr>
</thead>
<tbody>
<tr>
<td>p0u0</td>
<td>2886.6</td>
<td>-</td>
<td>0.8655</td>
<td>-</td>
</tr>
<tr>
<td>p1u0</td>
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<td>0.8993</td>
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<td>-23.4</td>
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<tr>
<td>p5u9995</td>
<td>2290.2</td>
<td>-20.7</td>
<td>0.9493</td>
<td>+9.7</td>
</tr>
</tbody>
</table>

\[
\gamma = \frac{\sum_i \left(1 - 0.5 \cdot \left|1 - \left(\frac{V_i}{V_{\text{mean}}}\right)\right\right) \cdot A_i}{\sum_i A_i}
\]

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Air-intake | Z-velocity @ Outlet

p0u0  p1u0  p1u9  p1u999  p5u9995

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Air Intake

• Significant improvements:
  - 20-25% pressure loss, +7-10% uniformity
Air Intake

- Significant improvements in system performance despite constrained highly complex design space
  - 20-25% pressure loss, 7-10% uniformity
- Issue
  - Some parts difficult to manufacture – requires interpretation
  - Due to explicit global minimum curvature specification which is not sensitive to local requirements
    - Too large minimum curvature produces poor objectives
    - Too small, noisy geometry

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Cabin Air Inlet

- Do728 cabin air inlet
- Steady incompressible
  - Similar uniformity index to existing design
  - Pressure drop -50%
Cabin Air Inlet

Adjoint optimized shape
-50% pressure loss
compared to original geometry.
Heat Exchanger Intake

- Automotive air intake / heat exchanger intake flow
- Steady incompressible
  - Pressure drop -15%
  - Uniformity +19%

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Summary

• Next generation geometric design aid based on adjoint technology
  ▪ 1-2 orders of magnitude faster than conventional methods (depending on number of parameters and objectives).
  ▪ Cost does not increase with number of parameters.

• Limitations
  ▪ Gradient based sensitivities – cannot always find global optima.
  ▪ Current surface representation method does not reliably produce easy to manufacture geometries.
  ▪ Adding new objectives requires deriving new boundary conditions and source terms for adjoint equations – complex process.
Looking ahead

• Level-Set based surface handling for improved manufacturability constraints
• Improved immersed boundary handling
• Surface based morphing
  ▪ More accurate surface representation
  ▪ Coupling to traditional morphing tools
• Scalar transport for mixing and heat transfer optimisation.