An Efficient Approach for CFD Topology Optimization of interior flows

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Agenda

• Introduction of FE-DESIGN
• Overview of Optimization Concepts
  ▶ Parametric Optimization
  ▶ Topology Optimization
• Application Examples
  ▶ Automotive HVAC Flow Splitter
  ▶ Intercooler Intake Hose
  ▶ Exhaust Gas Recirculation Cooler
• Summary
FE-DESIGN customers

Solutions Supporting the Product Development Process

Component design in early design phase

Design Improvement

Concept Improvement Validation Design Implementation Prototype Production

Process Capturing and Process Automation

Data-analysis and Optimization

FE-DESIGN – the optimization company

3rd ANSA & mETA International Conference
September 9-11, 2009, Porto Carras
Introduction to Parametric Optimization

- Restricted solution space
- Comparative high computational effort
- No restrictions with respect to the objective functions

Workflow of Parametric Optimization based on CFD Simulations

1. CFD model
   - CFD Solver
     - CFD Results
     - Optimizer
       - Modifies Parameters
         - Variation of Model Parameters
           - New CFD model
Workflow of Parametric Optimization based on Response Surface Models

- Alternative:
  - “Design of experiments” (DOE)
  - “Response surface model” (RSM)
  - Optimization based on RSM

Real Life is Highly Nonlinear

Conventional RSM  Advanced Meta-Models
Advanced Meta-Models are needed

Meta-Models
Challenges and Opportunities

- Conventional RSM („Response Surface Model“)
  - High number of design variables and complex system responses require many simulations
  - Local error estimation of the surrogate model is not supported

→ Optimization on conventional RSM is expensive and questionable
**Advanced Meta-Models**

- Local error estimation gives hints where to refine the model with additional training data
- Automated model update procedures are supported
- This assures reliable and verified optimization results
- Advanced meta-modeling techniques are provided as a one-click solution with an integrated optimization algorithm
- There is no expert knowledge needed, since the entire process of model selection and generation is completely automated
- The advanced methods are extremely flexible due to large diversity of integrated model formulations

→ Advanced Meta-Models are economically and give a deep insight into product behaviour

**Optimization of CAD-Parameters**

- Optimization problem is based on a parameterized Geometry (CAD, Preprocessor, ...)
- Geometric Variation is achieved by reconstruction of an individual geometry based on a given set of parameters
- Geometry parameters are varied automatically within a given range (optional)
Pros & Cons for Optimization of CAD-Parameters

- **Pros & Cons**
  - Optimization problem has to be parameterized
  - Restricted solution space
  - Identification of relevant influencing variables is not always easy
  - Comparative high computational effort
  - Easy export of optimization results to CAD
  - Many different techniques and algorithms are available
  - No restrictions with respect to the objective function
  - “Straight-forward approach”

Optimization of Morphing-Parameters

- Optimization problem is based on a meshed Geometry
Optimization of Morphing-Parameters

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- A number of Control Points and Basis Vectors are defined
- Geometric Variation is achieved by Mesh deformation within defined Morphing boxes
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Pros & Cons for Optimization of Morphing-Parameters

- **Pros & Cons**
  - Reconstruction and/or export of optimization results to CAD is not that easy
  - Morphing setup may be difficult, especially if nothing is known about the solution
  - More “creative freedom” compared to CAD-Parameter
  - **Complex Shape deformation possible with few parameters**
  - Larger solution space compared to CAD-Parameters
  - No restrictions apply with respect to the objective function
  - “Unconventional” Designs possible (Innovation!)
Introduction: Topology Optimization

- Optimization problem is based on the (meshed) available Design Space
- Geometric Variation is achieved by sedimenting individual cells
Introduction: Topology Optimization

- Optimization problem is based on the (meshed) available Design Space
- Geometric Variation is achieved by sedimenting individual cells
- An individual design proposal can be derived based on the collectivity of all free (= non-sedimented) cells
- General optimization schemes are not feasible
- **Optimality Criteria (OC) based schemes**

OC-based Topology Optimization

- **Optimality Criteria** methods can be seen as an “empirical approach”
- Consist of “knowledge” about properties of the optimum and a redesign rule (Controller-feedback approach)
- Are widely and successfully used in structural mechanics (“homogenization methods”)

![Diagram](image-url)
OC-based Topology Optimization: Example

- Example: The Optimality Criterium is to avoid flow recirculation

- Redesign Rule: Elimination of local backflow and recirculation by blocking out of backflow areas

- An achieved consequence is (for many technical flows) a reduction of pressure drop

Topology optimization with TOSCA Fluid

- Define the Design Space (e.g. CAD)
- Meshing as usual
- Define your Boundary Conditions
- Run the Optimization
Topology optimization with TOSCA Fluid

- Direct run time communication with the CFD solver
- Only one single CFD solver-run for complete optimization process

Optimized Channel Shape

- Free Flow
- Outflow 1
- Outflow 2
- Transition Area (defining new channel shape)
- Prevented Flow
- Inflow

→ suitable for large real world applications
Topology optimization with TOSCA Fluid

Example Animation:
Current optimization solution during convergence process

TOSCA Fluid – Process Integration

Result smoothing with TOSCA Fluid.smooth:
Topology Optimization Iso surface calculation, smoothing, data reduction Derived Verification/ CAD model

surface model (IGES, VRML, STL)
Topography Optimization

- **Pros & Cons**
  - Design-Reconstruction of optimization results is necessary (CAD)
  - Limited number of objective functions
  - Consideration of design space constraints and/or manufacturing restriction is straightforward
  - Easy setup and low modelling effort, no definition of CAD parameters, shape functions, morphing boxes, …
  - Very fast and effective (OC-based)
  - Maximum “freedom” within the design space to find a solution proposal
  - “Unconventional” Designs possible (Innovation!)
  - Optimization can be used as an initial design tool
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- Application Examples
  - Automotive HVAC Flow Splitter
  - Intercooler Intake Hose
  - Exhaust Gas Recirculation Cooler
- Summary
HVAC Flow Splitter Manifold (generic)

Dimensions = (0.2 x 0.14 x 0.12) m³
Fluid = AIR
Objective: Design Proposal with low pressure drop

- Standard Duct and available Design Space

- Objective: Design Proposal with low pressure drop

OUT2 (Flowsplit = 0.6)
OUT1 (Flowsplit = 0.4)

W_{in} = 5 m/s
HVAC Flow Splitter
Flow Design Space: Pathline and Pressure Drop at 5 m/s

Available Design Space

Original Part

Optimized Design Proposal
HVAC Flow Splitter
Results: Optimized Geometry, Pathline and Pressure Drop at 5 m/s

Pathlines coloured with velocity magnitude

<table>
<thead>
<tr>
<th>rel. mean Total Pressure Drop</th>
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<tbody>
<tr>
<td>1.00</td>
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<tr>
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Δp: 26 %

Application Example 2:
CFD Topology Optimization of an existing Intercooler Intake Hose
Introduction

Turbocharger System

Initial Design Proposal

Compressed Air Flow
Flow Performance of the Initial Design Proposal (2)

- exemplary local flow separation

Pathlines (colored with velocity magnitude)

Contours of Total Pressure Gradient (Magnitude), \( \text{pa/m} \)

\( | \nabla p_{\text{tot}} | \)

\( \rightarrow \) dissipative flow separation and recirculation zones

Optimization Results (1)

- Sedimented Zones
Result Analysis: Geometry

Initial Design  
optimized Design

Result Analysis: Pathlines (detail)  
(coloured with Velocity Magnitude)

Initial Design  
optimized Design
Result Analysis: Total Pressure Drop

- Comparison of the Total Pressure Drop

![Bar chart showing comparison of Initial Design and Optimized Design. Initial Design is 100%, Optimized Design is 79.6%.]

Application Example 3: Exhaust Gas Recirculation Cooler
EGR Cooler

Exhaust Gas Recirculation Systems → NOx-Abatement for internal combustion engines

Example Assembly

Functional diagramm

EGR Cooler
existing Design

- Simplified generic model

Hydraulic Heat Exchanger model as "porous zone" with preferential flow direction along the main flow axis

Air ($w_{in} = 3$ m/s)
EGR Cooler
Heat Exchanger Efficiency

Efficiency

Uniformity Index

Results for existing Designs

• “Standarddesign 1”

$\Delta p_{\text{tot}} = 9.5 \text{ pa}$

Uniformity Index = 0.81

Contours of Normal Velocity Magnitude at Outlet, m/s
EGR Cooler
Results for existing Designs (2)

- **“Standarddesign 1”**
  \[ \Delta p_{\text{tot}} = 9.5 \text{ pa} \]
  Uniformity Index = 0.81

- **“Standarddesign 2”**
  \[ \Delta p_{\text{tot}} = 6.4 \text{ pa} \]
  Uniformity Index = 0.93

- Optimization Objective: Homogenization of cross section velocity distribution at the outlet

EGR Cooler
Design Space

- Used Design space and Model settings

Boundary Conditions:
- Inflow = PRESSURE
- Outflow = INLET, \( w_{\text{out}} = -3 \text{ m/s} \)

Fluid AIR
- Isothermal, turbulent, stationary, incompressible
  - \( \eta = 1.81 \cdot 10^{-6} \text{ kg/(m·s)} \)
  - \( \rho = 1.205 \text{ kg/m}^3 \)

TOSCA Fluid Version 1.0.0 beta

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**EGR Cooler**

**Results: Optimized Design**

- Extracted New Design Proposal

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**Tosca Fluid Version 1.0.0 Beta**

Backflow Tolerance 0.5

Extraktion: velocity absolute

velocity iso surface 0.25 m/s

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**EGR Cooler: Comparison of Designs**

- Cross sectional velocity uniformity and heat exchanger efficiency

<table>
<thead>
<tr>
<th>Design Variante</th>
<th>Relative Total Pressure Drop</th>
<th>Relative Exchanger Efficiency</th>
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<tbody>
<tr>
<td>Standard 1</td>
<td>0.66</td>
<td>0.67</td>
</tr>
<tr>
<td>Standard 2</td>
<td>1.00</td>
<td>0.87</td>
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<tr>
<td>Optimized</td>
<td>0.96</td>
<td>0.96</td>
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Transfer Efficiency

+11% resp. + 45%

Pressure Drop

-19% resp. - 46%
Summary

- Topology Optimization of arbitrary interior flow domains using Optimality Criteria Methods
- Possible Optimization Objectives are
  - Reduction of total pressure drop
  - Homogenization of cross section velocity distribution
  - and more…
- Only one single CFD solver-run for a complete optimization process is needed
- Significantly faster than automatic parametric Optimization
- Giant solution space → Innovation!
- Actual available for STAR-CD and ANSYS FLUENT
- “Initial Design Tool” to find modified Design proposals with reduced energy dissipation by backflow elimination
- Gives good proposals for subsequent fine tuning e.g. via parametric morphing