NON-PARAMETRIC SHAPE OPTIMIZATION IN INDUSTRIAL CONTEXT

Michael Böhm, Peter Clausen
Overview

- Introduction / FE-Design
- Optimization in Industry and Requirements
- Shape optimization loops in Fluid Dynamics
- Shape optimization loops in Structural Mechanics
- Summary and Future developments
FE-DESIGN
the optimization company

TOSCA Structure

TOSCA Fluid

Customization

Process Automation

Multidisciplinary Optimization

Visualization/Evaluation
FE-DESIGN

the optimization company

TOSCA Structure

Process Automation

Software Development and Engineering Services

TOSCA Fluid

Multidisciplinary Optimization

Customization

Visualization/Evaluation
Industrial development and requirements

- Sensitivity based parameter-free shape optimization
- Multi criteria optimization
- Optimization with respect to (manufacturing) constraints
Industrial development and requirements

- Sensitivity based parameter-free shape optimization
- Multi criteria optimization
- Optimization with respect to (manufacturing) constraints

Challenges to get optimization “used” in the industrial development process

- Optimization processes have to fit into the PDP
- The designer / engineer has to be guided through the optimization
- The approach should be easy to use and stable
Industrial Optimization Loop

Engineering Loop
Industrial Optimization Loop

Designspace for Topo Optimization

Engineering Loop
Industrial Optimization Loop

Designspace for Topo Optimization

Result Cell Set After Topo Optimization

Engineering Loop
Industrial Optimization Loop

Designspace for Topo Optimization

Result Cell Set After Topo Optimization

Extracted Smooth Surface

Engineering Loop

FE-DESIGN – the optimization company
Industrial Optimization Loop

- Designspace for Topo Optimization
- Result Cell Set After Topo Optimization
- Extracted Smooth Surface
- Initial Shape Model
- Engineering Loop

FE-DESIGN – the optimization company

Corporate proprietary, Approval for distributing and copying required
Industrial Optimization Loop

- Designspace for Topo Optimization
- Result Cell Set After Topo Optimization
- Engineering Loop
  - Final Shape Result
  - Initial Shape Model
  - Extracted Smooth Surface
  - (Colored with point displacement compared to initial shape model)
Industrial Optimization Loop

Designspace for Topo Optimization

Result Cell Set After Topo Optimization

Engineering Loop

Framework

Final Shape Result

Extracted Smooth Surface

Initial Shape Model

"Optimization modules"

CFD iterations

(primal problem)

dual problems

Every n<sup>th</sup> CFD iteration

(Colored with point displacement compared to initial shape model)

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Industrial Non-parametric Shape Optimization
Industrial Non-parametric Shape Optimization

Actual Fluid Development

- FlowHead
- Commercial Adjoint Sensitivity Approaches for Industry
Industrial Non-parametric Shape Optimization

Actual Fluid Development

- Commercial Adjoint Sensitivity Approaches for Industry

Actual Structure Development

- Combining Controller and Sensitivity Information
- Stress Sensitivities for Shape Optimization with Commercial Solvers
Fluid Dynamics
Adjoint Method

Automatic Differentiation

- Necessary change of $s_i$ unknown

- Not available in commercial CFD solvers
**Adjoint Method**

**Automatic Differentiation**

- Necessary change of $s_i$ unknown

Variation of the objective

\[ \delta J = \frac{\partial J}{\partial y} \delta y + \frac{\partial J}{\partial s} \delta s \]

Variation of the NS System

\[ \delta R = 0 = \frac{\partial R}{\partial y} \delta y + \frac{\partial R}{\partial s} \delta s \]

Lagrange System

\[ \delta \hat{J} = \left( \frac{\partial J}{\partial y} \right) \delta y + \left( \frac{\partial J}{\partial s} \right) \delta s + p^T \left( \frac{\partial R}{\partial y} \right) \delta y + \left( \frac{\partial R}{\partial s} \right) \delta s \]

- $p^T$, Lagrange Multiplier

\[ \delta \hat{J} = \left[ \frac{\partial J}{\partial s} + p^T \left( \frac{\partial R}{\partial s} \right) \right] \delta s + \left[ \frac{\partial J}{\partial y} + p^T \left( \frac{\partial R}{\partial y} \right) \right] \delta y \]

$p^T$ choose in a way that:

\[ \left( \frac{\partial J}{\partial y} + p^T \left( \frac{\partial R}{\partial y} \right) \right) = 0 \]

- additionally PDE System $Ax - b = 0$

"backward differentiation"
Adjoint Method

Automatic Differentiation

- Necessary change of $s_i$ unknown

Variation of the objective

$$\frac{\partial J}{\partial y} \delta y + \frac{\partial J}{\partial s} \delta s$$

Variation of the NS System

$$\delta R = 0 = \left( \frac{\partial R}{\partial y} \right) \delta y + \left( \frac{\partial R}{\partial s} \right) \delta s$$

Lagrange-System

$$\delta \tilde{J} = \left( \frac{\partial J}{\partial y} \right) \delta y + \left( \frac{\partial J}{\partial s} \right) \delta s + \mathbf{p}^T \left( \left( \frac{\partial R}{\partial y} \right) \delta y + \left( \frac{\partial R}{\partial s} \right) \delta s \right)$$

- $\mathbf{p}^T$, Lagrange-Multiplier

Continuous Adjoint

- “Easy” available in OpenFOAM

PDE System $A\mathbf{x} - \mathbf{b} = 0$

- $\mathbf{p}^T$ choose in a way that:

$$\left( \frac{\partial J}{\partial y} \right) + \mathbf{p}^T \left( \frac{\partial R}{\partial y} \right) = 0$$
Framework – Shape optimization

Engineering Loop

Initial Shape Model

XML parameter file 3d-sbend-shape.xml

OpenFOAM case 3d-sbend-shape.foam
Framework – Shape optimization

Engineering Loop

Modules

Mesh regularization

Framework

Design cycles

CFD iterations

"Optimization modules"

CFD solver

primal problem

dual problems

Every n\textsuperscript{th} CFD iteration

XML parameter file
3d-sbend-shape.xml

OpenFOAM case
3d-sbend-shape.foam

Initial Shape Model

FE-DESIGN – the optimization company
Framework – Shape optimization

Engineering Loop

Modules

- Design cycles
- CFD iterations
- "Optimization modules"
- CFD solver
  - primal problem
  - dual problems
- Framework
- Every n\textsuperscript{th} CFD iteration
- Mesh regularization
- XML parameter file
  - 3d-sbend-shape.xml
- OpenFOAM case
  - 3d-sbend-shape.foam

Final Shape Result

(Colored with point displacement compared to initial shape model)

Initial Shape Model

FE-DESIGN – the optimization company
Framework - Capabilities (1)

- Different optimization algorithms
  - Steepest descent (unconstraint)
  - Method of moving asymptotes (constraint + unconstraint)
Framework - Capabilities (1)

- Different optimization algorithms
  - Steepest descent (unconstraint)
  - Method of moving asymptotes (constraint + unconstraint)

- Different filter and regularization methods available
  - In-plane regularization (TU München)
  - Out-of-plane filtering (TU München)
  - Laplace regularization
  - Sigmund filter (for surfaces and volumes)
  - Design - Nondesign transition filter

In-plane regularization
- Cost functions can be used as objective function
  \[ \min(f(x)) \]
- Cost functions can be used as constraints
  \[ g(x) \leq g^* \]
- Cost functions can be combined
  \[ f(x) = a * f_1(x) + b * f_2(x) \]

**Objective**
\[ \min(\Delta P + c_1 * U) \]

**Constraint**
\[ V \leq c_2 * V_0 \]

U – Uniformity
V – Volume
\( \Delta P \) – Total Pressure Loss
Framework - Capabilities (2)

- Cost functions can be used as objective function
  \[ \min( f(x) ) \]
- Cost functions can be used as constraints
  \[ g(x) \leq g^* \]
- Cost functions can be combined
  \[ f(x) = a * f_1(x) + b * f_2(x) \]

**Objective**
\[ \min( \Delta P + c_1 * U ) \]
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**Objective**
\[ \min( \Delta P ) \]
**Constraints**
\[ U \leq U^* \]
\[ V \leq c_2 * V_0 \]

U – Uniformity
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\(\Delta P\) – Total Pressure Loss
Framework - Capabilities (2)

- Cost functions can be used as objective function
  \[ \min (f(x)) \]
- Cost functions can be used as constraints
  \[ g(x) \leq g^* \]
- Cost functions can be combined
  \[ f(x) = a \cdot f_1(x) + b \cdot f_2(x) \]

**Objective**

\[ \min (\Delta P + c_1 \cdot U) \]

**Constraint**

\[ V \leq c_2 \cdot V_0 \]

**Objective**

\[ \min (\Delta P) \]

**Constraints**

\[ U \leq U^* \]
\[ V \leq c_2 \cdot V_0 \]

**Objective**

\[ \min (U) \]

**Constraints**

\[ \Delta P \leq P^* \]
\[ V \leq c_2 \cdot V_0 \]

U – Uniformity
V – Volume
\( \Delta P \) – Total Pressure Loss
External Shape Optimization – SAE Body Example

Design zone

SAE Car

30 m/s

Optimization Progress

Objective Value

Iteration

Optimization with respect to Pressure Loss

SAE Car

U Magnitude

0.046 0.07 39.34

0.007 20 30 39.14
Summary and Outlook

- First implementations have been tested on industrial applications
- A full commercial adjoint based optimization solution is still not ready
Summary and Outlook

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- A full commercial adjoint based optimization solution is still not ready

Necessary are:

- Further developments of industrial relevant adjoints

Further developments:

- Improvement of optimization algorithms and stability
- Advanced mesh regularization for internal mesh
- Adding manufacturing constraints for shape
- …
Shape optimization of the Stabilizer Bar Link for the front Axle of the A8 II

Initial geometry

Optimized coupling link

Structure Mechanics
Stabilizer Bar Link from Audi A8 - Example

- Verification of result by recalculation with Pro/Mechanica:
  - TOSCA-result (freeform surface): Stress reduction by 30 %
  - Modified Radius: Stress reduction only by 18 %

- Transfer into CAD and reconstruction

- Assembly in the new A8
TOSCA Structure.shape: Objective and Constraints

Non-parametric shape optimization defined simply via node groups

- No need to create shape basis vectors!
- Filtering of sensitivities ensures smooth surface and removes mesh dependencies
TOSCA Structure.shape: Objective and Constraints

Non-parametric shape optimization defined simply via node groups

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Objective function and constraints:

- Minimization of combinations of equivalent stress values (various stress hypothesis available)
- Maximization of selected natural frequencies
- Specification of a volume constraint
TOSCA Structure.shape

- Few optimization cycles are needed
  - Number of cycles is independent of number of design variables!

- Mesh ‘morphing’ and mesh smoothing in each optimization cycle

- Optimization using results of a durability analysis (FEMFAT, fe-safe, nCode DesignLife, Virtual.Lab Durability, MSC.Fatigue, inhouse codes....)

- Support of **nonlinear analysis**
  - Contact
  - Large deformation
  - Nonlinear Material
TOSCA Structure.shape
Manufacturing Restrictions

- Surface-based manufacturing constraints
  - Demolding
  - Stamping
  - Extrusion
  - Turning
  - Minimum and maximum member size

- Symmetry constraints

- Penetration checks to neighbouring parts

- Design variable constraints
  - Restriction of the optimization domain
  - Restriction and coupling of nodal degrees of freedom
  - Restriction of nodal movement to slide surface etc.
“Controller-Sensitivity Method” - Theory

- How to get sensitivity information from commercial solvers?
“Controller-Sensitivity Method” - Theory

- How to get sensitivity information from commercial solvers?
- For responses like compliance and displacements assuming $df/da = 0$ is sufficient
“Controller-Sensitivity Method” - Theory

- How to get sensitivity information from commercial solvers?

If \( \lambda \) is chosen such that

\[
K\lambda = \frac{\partial \Psi}{\partial u}
\]  

(1)

We obtain the adjoint equation (assuming symmetry: \( K = K^T \)):

\[
\frac{d\Psi}{da} = \frac{\partial \Psi}{\partial a} - \lambda^T \left( \frac{dK}{da} u - \frac{df}{da} \right)
\]  

(2)

We call the new method for shape optimization ‘controller-sensitivity method’ were we state the optimization problem:

\[
\min (f(u, a))
\]  

(3)

s.t. \( Ku = f \)  

(4)

\( g_i(u, a) \leq g_i^* \)  

(5)

\( a_{min} < a < a_{max} \)  

(6)

\( f \) is a function supported by the controller approach (stress, strain, fatigue, ... )

To solve this problem we need the sensitivities \( \frac{df}{da} \) and \( \frac{dg_i}{da} \). Our trick is to set \( \frac{df}{da} = \text{controller values} \). In the following we concentrate on the sensitivity calculation for the constraints, \( \frac{dg_i}{da} \).
“Controller-Sensitivity Method” - Theory

- How to get information from commercial solvers?
- For responses like compliance and displacements assuming $\frac{df}{da} = 0$ is sufficient
- For strains and stresses is it not sufficient and we set $\frac{df}{da} = \text{controller values}$
“Controller-Sensitivity Method”

Conrod with 3 loadcases
- LC1 tension
- LC2 compression
- LC3 stiffness in the “weak” axis direction

- Typical industrial application size
  - 68068 linear tets
  - 15102 nodes (45306 DOFs)

- Solved in NX-Nastran

Controller only result in TOSCA Structure
“Controller-Sensitivity Method”

**Objective**
- Minimization/ homogenization of von Mises stress in LC1 and LC2 (using controller)

**Constraint**
- Maximum displacement for LC3
"Controller-Sensitivity Method"

Objective
- Minimization/ homogenization of von Mises stress in LC1 and LC2 (using controller)

Constraint
- Maximum displacement for LC3
“Controller-Sensitivity Method”

Objective

- Minimization/homogenization of von Mises stress in LC1 and LC2 (using controller)

Constraint

- Maximum displacement for LC3

Constraint is kept for CTRL-SENS
Summary and Outlook

- Sensitivity and controller approaches have been successfully coupled
- Constraints can be kept more effectively compared to a controller only approach
Summary and Outlook

- Controller-Sensitivity approach has been successfully coupled
- Constraints can be kept more effectively compared to a controller only approach

Further developments:
- Extend constraints for the Method (Project: ShapeOpt2CAD)
- Support Liner Stress Constraints
- Extend Methods to More Element Types
- ...
Post-processing – CAD back transfer

CAD re-construction

A very important step is how to get the optimized geometry back into a CAD system

IGES re-construct
- The advantage of IGES cuts are big and simple shapes
- Depending on the number of cuts a de-featuring is possible

STL re-construct
- The shape size depends on the local surface angle and
- All features are kept

Re-construct based on IGES cuts

Re-construct based on STL data
Thank you for your attention