Aerodynamic Optimization of a Low-Pressure Axial Fan Using Adjoint Computational Fluid Dynamics

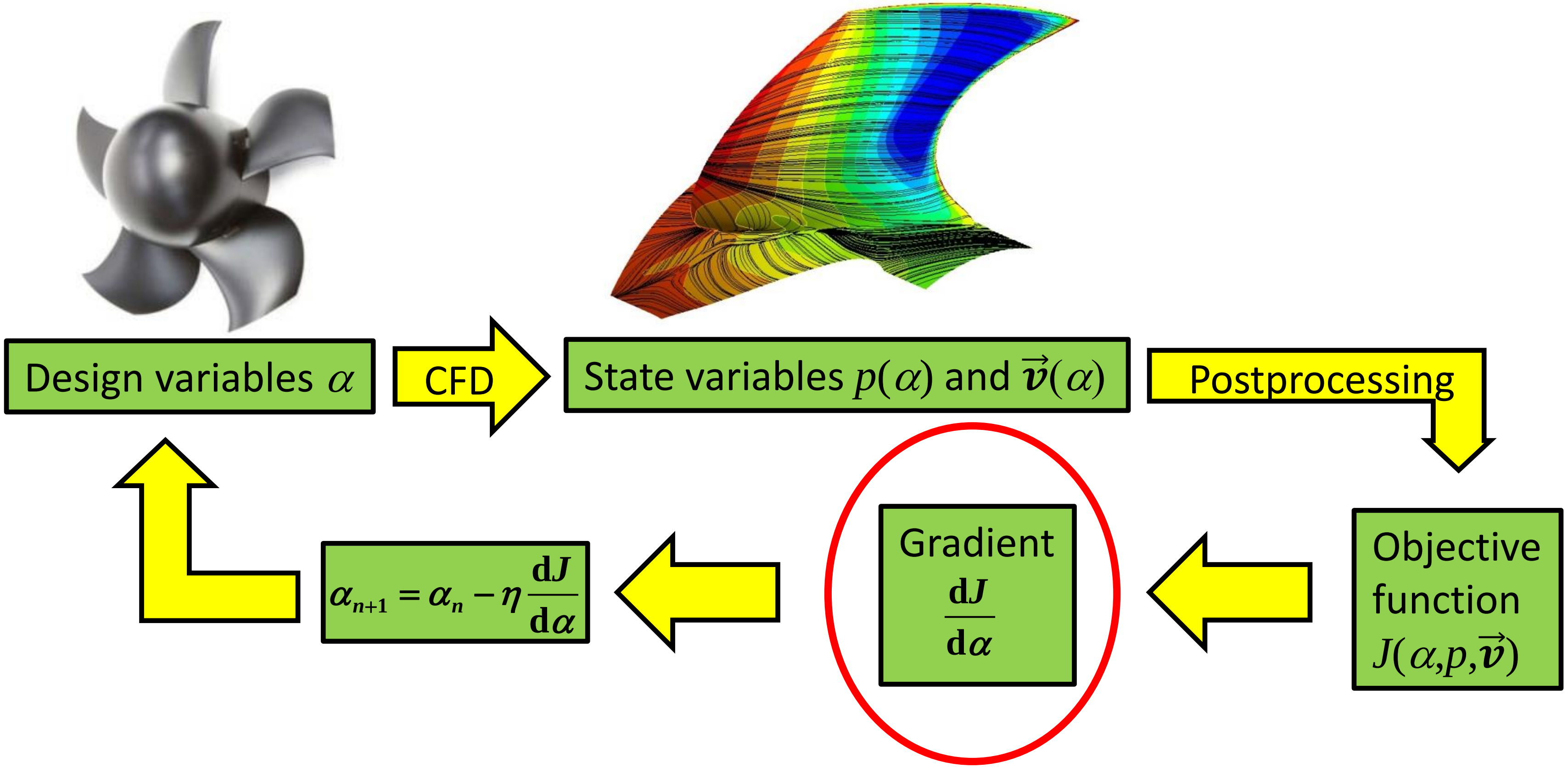
Konrad BAMBERGER
UNIVERSITY OF SIEGEN

Thomas CAROLUS
UNIVERSITY OF SIEGEN

27 – 29 June 2022, Senlis (France)

Introduction

Typical CFD-based optimization loop



Design variables α

CFD

State variables $p(\alpha)$ and $\vec{v}(\alpha)$

Postprocessing

Objective function $J(\alpha, p, \vec{v})$

Gradient $\frac{\mathrm{d}J}{\mathrm{d}\alpha}$

$\alpha_{n+1} = \alpha_n - \eta \frac{\mathrm{d}J}{\mathrm{d}\alpha}$

Methodology

Standard gradient computation

- objective function depends on the state variables which in turn depend on the design variables

$$\frac{\mathrm{d}J}{\mathrm{d}\alpha} = \frac{\partial J}{\partial \alpha} + \frac{\partial J}{\partial \vec{v}} \frac{\mathrm{d}\vec{v}}{\mathrm{d}\alpha} + \frac{\partial J}{\partial p} \frac{\mathrm{d}p}{\mathrm{d}\alpha}$$

- the state variables need to be recomputed for each change of the design variables

  → very high computational effort

  and/or

  → limitation of the number of free design variables

Methodology

Adjoint method for gradient computation

- Lagrange formulation of the objective function

minimize $L = J + \int_{\Omega} (\vec{u}, q) R \, \mathrm{d}\Omega$

$$\frac{\mathrm{d}L}{\mathrm{d}\alpha} = \frac{\partial L}{\partial \alpha} + \frac{\partial L}{\partial \vec{v}} \frac{\mathrm{d}\vec{v}}{\mathrm{d}\alpha} + \frac{\partial L}{\partial p} \frac{\mathrm{d}p}{\mathrm{d}\alpha}$$

- select $\vec{u}$ and q such that

$$\frac{\partial L}{\partial \vec{v}} \frac{\mathrm{d}\vec{v}}{\mathrm{d}\alpha} + \frac{\partial L}{\partial p} \frac{\mathrm{d}p}{\mathrm{d}\alpha} = 0 \quad \text{and hence} \quad \frac{\mathrm{d}L}{\mathrm{d}\alpha} = \frac{\partial L}{\partial \alpha}$$

- the computation of $\vec{u}$ and q is very similar to the computation of $\vec{v}$ and p

➔ **Only one CFD simulation for an arbitrary number of design variables!!!**

Objectives of the present work

A) Implementation of the adjoint method in OpenFOAM (specialized for fan optimization)

B) Application of the adjoint method to a low-pressure axial fan

Methodology

Existing adjoint implementation in OpenFOAM

- Name: *adjointShapeOptimizationFoam*
- steady-state (RANS), incompressible
- loss terms for porous cells
  → **the porosity of each cell is a design variable!**
- primal Navier-Stokes equations

$$\left(\vec{v}\cdot\nabla\right)\vec{v}+\nabla p+\nabla\cdot\left(2\nu\mathrm{D}\left(\vec{v}\right)\right)+\alpha\vec{v}=0$$

$$-\nabla\vec{v}=0$$

- adjoint Navier-Stokes equations (derivation see e.g. Othmer, 2008)

$$\nabla\vec{u}\cdot\vec{v}+\left(\vec{v}\cdot\nabla\right)\vec{u}-\nabla q+\nabla\cdot\left(2\nu\mathrm{D}\left(\vec{u}\right)\right)-\alpha\vec{u}-\cancel{\frac{\partial J_{\Omega}}{\partial\vec{v}}}=0$$

$$\nabla\vec{u}-\cancel{\frac{\partial J_{\Omega}}{\partial p}}=0$$

Modified adjoint implementation in OpenFOAM

- additional source terms for the rotating frame of reference
- primal Navier-Stokes equations

$$\left(\vec{v}\cdot\nabla\right)\vec{v}+\nabla p+\nabla\cdot\left(2\nu\mathrm{D}\left(\vec{v}\right)\right)+\alpha\vec{v}$$

$$+\underbrace{\vec{\omega}\times\left(\vec{\omega}\times\vec{r}\right)}_{\text{centrifugal}}+\underbrace{2\vec{\omega}\times\vec{v}}_{\text{Coriolis}}=0$$

$$R_4=-\nabla\vec{v}$$

- adjoint Navier-Stokes equations

$$\nabla\vec{u}\cdot\vec{v}+\left(\vec{v}\cdot\nabla\right)\vec{u}-\nabla q+\nabla\cdot\left(2\nu\mathrm{D}\left(\vec{u}\right)\right)$$

$$-\alpha\vec{u}+2\vec{\omega}\times\vec{u}-\cancel{\frac{\partial J_{\Omega}}{\partial\vec{v}}}=0$$

$$\nabla\vec{u}-\cancel{\frac{\partial J_{\Omega}}{\partial p}}=0$$

Methodology

Adjoint outlet boundaries

- primal boundary conditions:
    - prescribed pressure
    - zero velocity gradient
- adjoint boundary conditions (derivation see e.g. Othmer, 2008):

$$q = \vec{u} \cdot \vec{v} + u_n v_n + \nu \left(\vec{n} \cdot \nabla \right) u_n + \frac{\partial J_\Gamma}{\partial v_n}$$

$$0 = v_n \vec{u}_t + \nu \left(\vec{n} \cdot \nabla \right) \vec{u}_t + \frac{\partial J_\Gamma}{\partial \vec{v}_t}$$

Adjoint inlet and wall boundaries

- primal boundary conditions:
    - prescribed velocity
    - zero pressure gradient
- adjoint boundary conditions (derivation see e.g. Othmer, 2008):

$$\vec{u}_t = 0$$

$$u_n = -\frac{\partial J_\Gamma}{\partial p}$$

$$\vec{n} \cdot \nabla q = 0$$

Methodology

Objective function J_1: Power maximization

$$J_1 = -\int_{\Gamma_{\text{inlet}}} \left(p + \frac{\rho}{2}\vec{v}\cdot\vec{v} \right) v_n \, \mathrm{d}\Gamma$$

- BC at outlet

$$q = \vec{u}\cdot\vec{v} + u_n v_n + \nu\left(\vec{n}\cdot\nabla\right)u_n + \cancel{\frac{\partial J_\Gamma}{\partial v_n}}$$

$$0 = v_n \vec{u}_t + \nu\left(\vec{n}\cdot\nabla\right)\vec{u}_t + \cancel{\frac{\partial J_\Gamma}{\partial \vec{v}_t}}$$

- BC at inlet and walls

$$\vec{u}_t = 0$$

$$\boxed{u_n = -\frac{\partial J_\Gamma}{\partial p}}$$

$$\vec{n}\cdot\nabla q = 0$$

Objective function J_2: Efficiency maximization at given flow power

- implemented by trying to minimizing the power required to drive the fan while maximizing the flow power

$$J_2 = J_1 - \int_{\Gamma_{\text{blade/hub}}} \vec{\omega}\cdot\left(\vec{r}\times\vec{n}\right)p \, \mathrm{d}\Gamma + P_{\text{shaft,viscous}}$$

- velocity BC at the blade and hub:

$$\boxed{u_n = -\frac{\partial J_2}{\partial p} = \vec{\omega}\cdot\left(\vec{r}\times\vec{n}\right)}$$

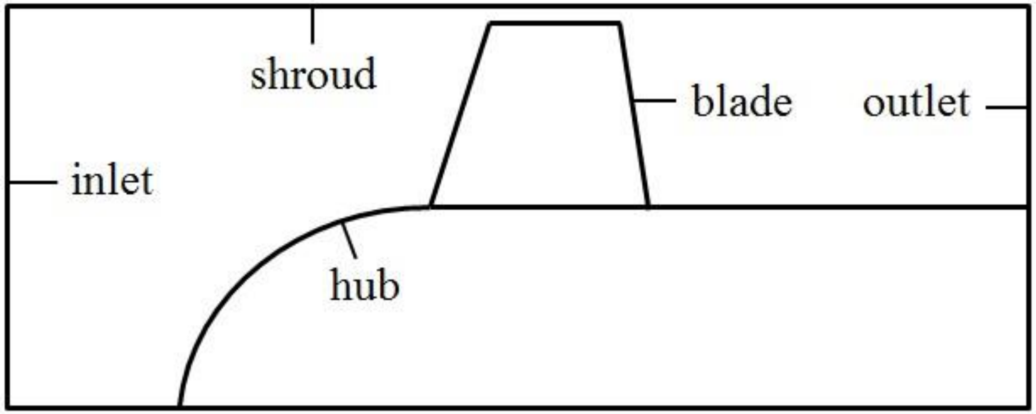
- all other BCs equivalent to J_1

Baseline Fan

Description of the baseline fan

- designed with the blade element momentum theory
- five blades
- hub-to-tip ratio $\nu = 0.45$
- non-dimensional design point:
  - $\varphi = 0.195$
  - $\psi_{ts} = 0.165$
- all simulations and experiments performed at
  - $D = 300$ mm
  - $N = 3000$ rpm

Prototype



CFD model

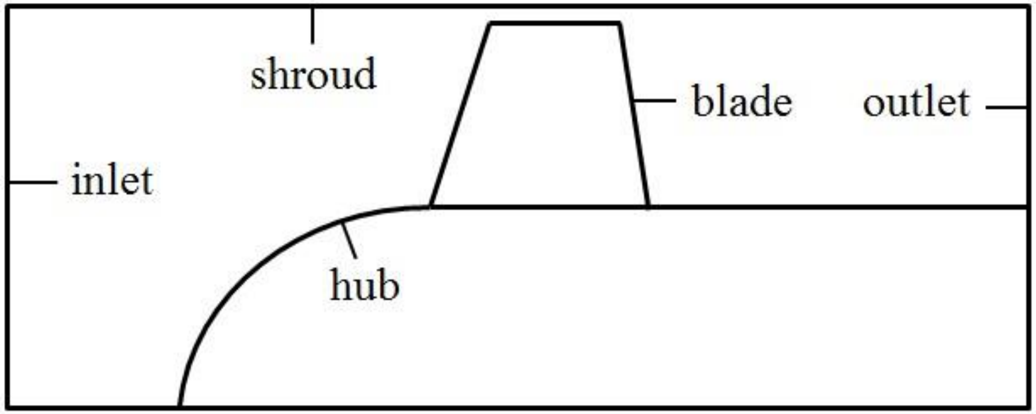
CFD Setup

Grid generation for the primal and adjoint CFD simulation

- created with cfMesh 1.1
- approx. 1.2 mostly hexahedral elements
- refinement near the walls, $y^+ \approx 20$

Turbulence properties for the primal and adjoint CFD simulation

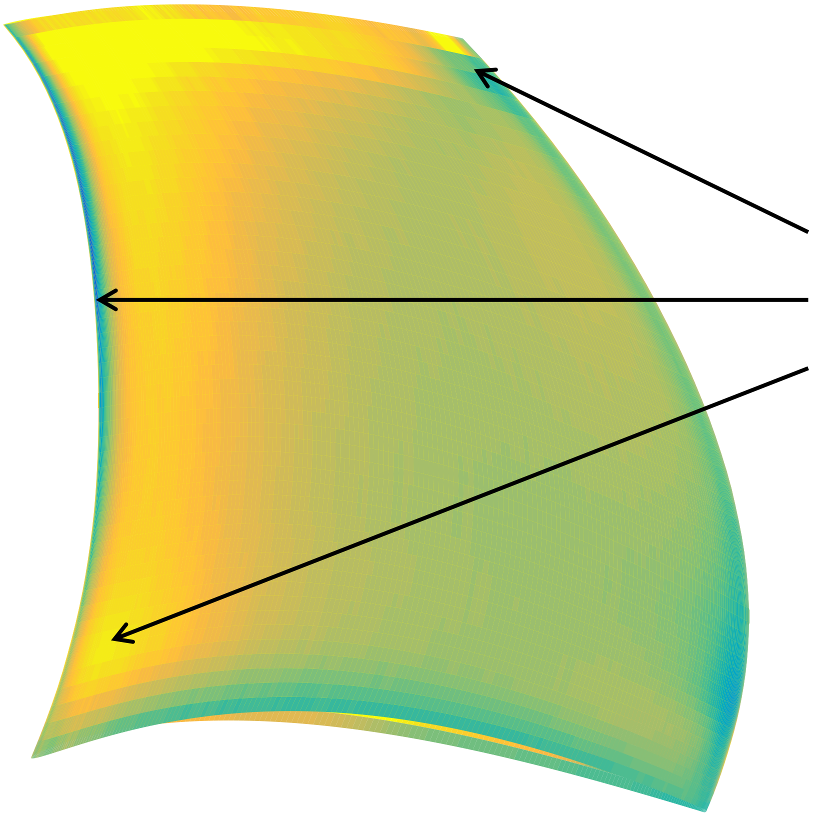
- k-ω SST turbulence model
- 5 % turbulence intensity at the inlet



CFD model

Results (1): Surface Sensitivity Maps on the Pressure Side

blue = „pull out“
yellow = „push in“



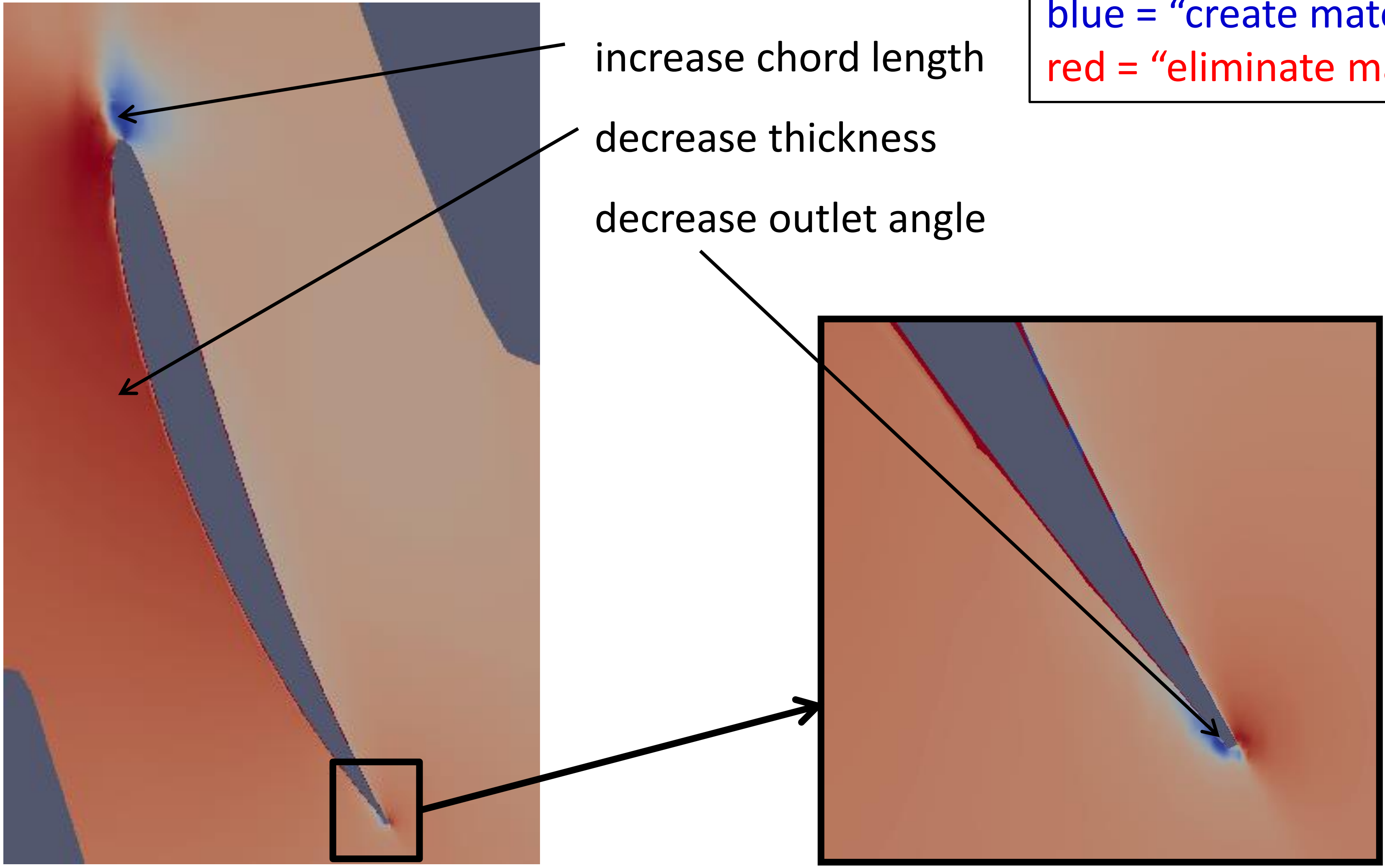
increase exit angle

increase chord length

decrease thickness

Results (2): Volume Sensitivity Maps

blue = “create material”
red = “eliminate material”

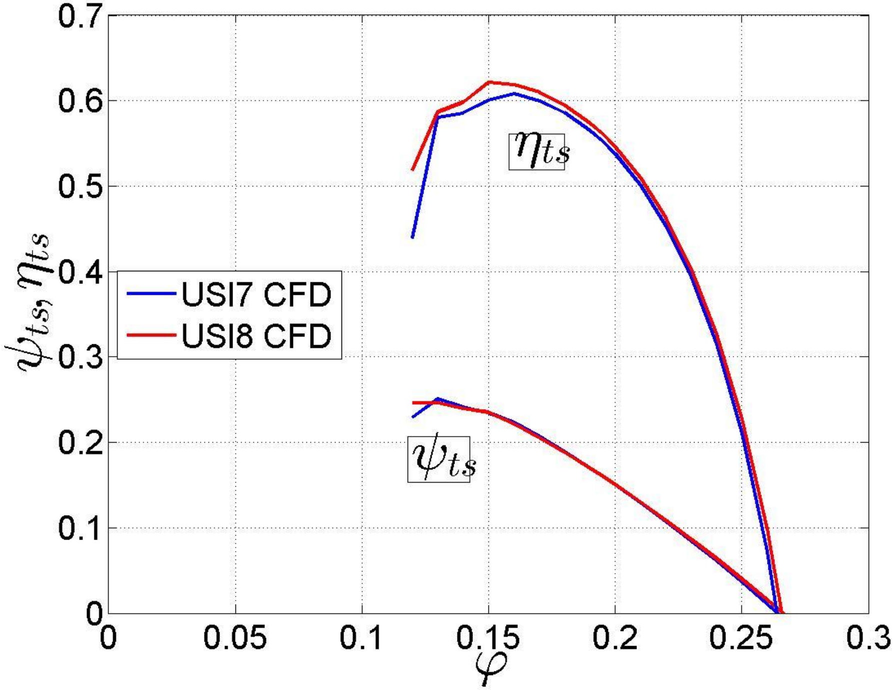


increase chord length

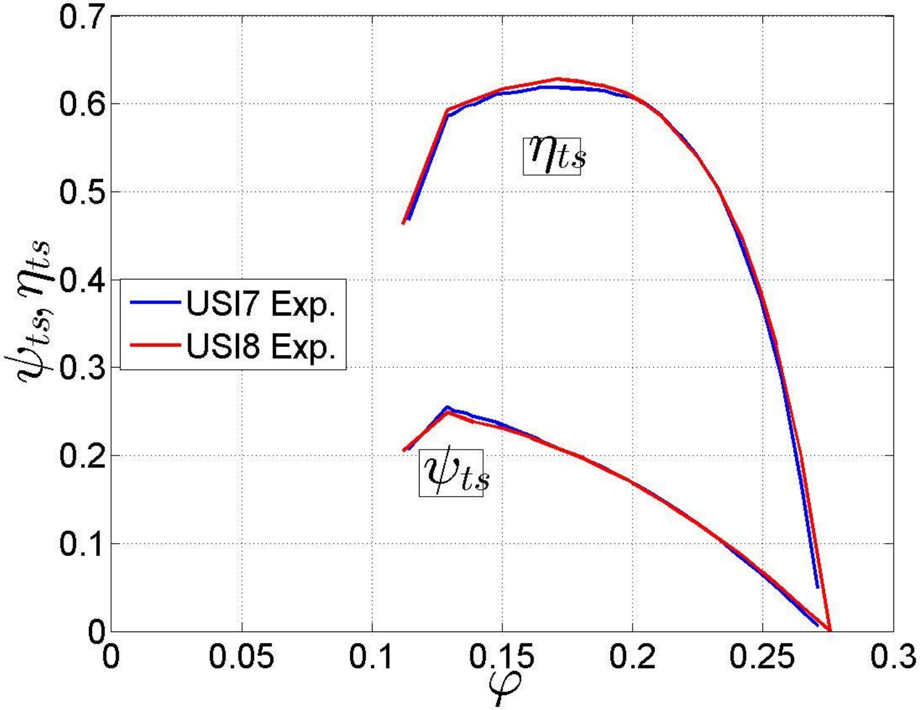
decrease thickness

decrease outlet angle

Results (3): Performance Curves



CFD



Measurement

- The optimized fan is named „USI8“. It was obtained after four optimization loops.
- As intended, the pressure curves of USI7 and USI8 are identical while the efficiency of USI8 is higher
- The improvement in efficiency is confirmed by experiments with CNC-milled prototypes. The gain, however, is smaller than expected

Summary and Conclusions

Major Achievements

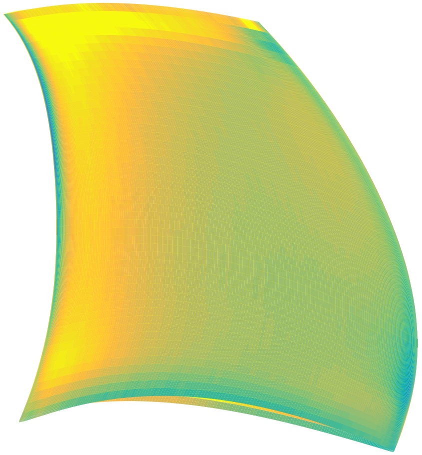
- The adjoint solver of OpenFOAM was extended for rotating frames of reference
- Adjoint boundary conditions for the aerodynamic optimization of fans were implemented
- A strategy to interpret the sensitivity maps was implemented
- The methodology was successfully applied to a low-pressure axial fan

But why are the improvements so small???

a) Was the baseline fan too good?

b) Are there numerical issues such as a grid dependency?

c) Did we misinterpret the sensitivity maps?



Thanks for your attention!