Aeroacoustic Optimization of an Axial Fan with Variable Blade Loading

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Objectives

- minimize selected bands of the acoustic spectrum
- maximize aerodynamic efficiency
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- maximize aerodynamic efficiency

This is performed for a fan with varying blade geometry (i.e. each blade is loaded differently).
Traditional development cycle for small axial fans

1. Design the blade geometry
2. Assess aerodynamic performance via CFD
3. Assess aeroacoustic performance via physical prototypes
Traditional development cycle for small axial fans

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3. Assess aeroacoustic performance via physical prototypes

Shortcomings:
• Spurious noise of physical prototypes
  • imperfect rotor dynamics
  • eccentricity of the fan
  • Vibration of the bearing system
  • Noise due to secondary flow through the cooling channels
• Low geometrical resolution of rapid prototyping
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To avoid this tedious optimization procedure
 augmentation of design process with aeroacoustic simulation
Variable Blade Loading

Blade parameterization by averaged swirl at trailing edge for hub and shroud:

\[ r \cdot \overline{c_u} = \frac{N}{2\pi} \int_0^{2\pi/N} r \cdot c_u \, d\theta \]
Variable Blade Loading

Blade parameterization by averaged swirl at trailing edge for hub and shroud:

\[ r \cdot \bar{c}_u = \frac{N}{2\pi} \int_0^{\frac{2\pi}{N}} r \cdot c_u d\theta \]

From this, the blade loading may be obtained:

\[ \Delta p = \frac{2\pi}{N} \rho w_{mb} \frac{\partial (r \cdot \bar{c}_u)}{\partial m} \]
Variable Blade Loading

PARAMETERS FOR EVOLUTIONARY OPTIMIZATION
Averaged swirl $r \overline{C_u}$ at trailing edge for hub and shroud
Variable Blade Loading

PARAMETERS FOR EVOLUTIONARY OPTIMIZATION

Averaged swirl $r\bar{c}_{u}$ at trailing edge for hub and shroud
Variable Blade Loading

PARAMETERS FOR EVOLUTIONARY OPTIMIZATION

Averaged swirl $r\overline{c_u}$ at trailing edge for hub and shroud

$r\overline{c_u}$ is specified independently for 7 individual blades at hub and shroud → 14 parameters
Winglet Parameterization

PURPOSE OF THE WINGLET: control the tip vortex

- Vortex may collide with the adjacent blade → lead to vibration and associated noise production
- Vortex can restrict the flow → decrease the aerodynamic performance
1. Cut the blade with a cylinder of diameter 0.8 D → cross section $\lambda$
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2. Project $\lambda$ orthogonal to cylindrical surface of diameter D → cross section $\mu$
Winglet Parameterization

1. Cut the blade with a cylinder of diameter 0.8 D \rightarrow \text{cross section } \lambda
2. Project \lambda \text{ orthogonal to cylindrical surface of diameter D } \rightarrow \text{cross section } \mu
3. \Phi_1(\theta): \text{Rotation of } \mu \text{ around } \xi \rightarrow \mu_1
Winglet Parameterization

1. Cut the blade with a cylinder of diameter 0.8 D → cross section $\lambda$
2. Project $\lambda$ orthogonal to cylindrical surface of diameter D → cross section $\mu$
3. $\Phi_1(\theta)$: Rotation of $\mu$ around $\xi$ → $\mu_1$
4. $\Phi_2(\zeta)$: Rotation of $\mu_1$ around $\chi$ → $\mu_2$
Winglet Parameterization

1. Cut the blade with a cylinder of diameter 0.8 D → cross section \( \lambda \)
2. Project \( \lambda \) orthogonal to cylindrical surface of diameter D → cross section \( \mu \)
3. \( \Phi_1(\theta) \): Rotation of \( \mu \) around \( \xi \) → \( \mu_1 \)
4. \( \Phi_2(\zeta) \): Rotation of \( \mu_1 \) around \( \chi \) → \( \mu_2 \)
5. \( \Phi_3(\sigma) \): Translation of \( \mu_2 \) along \( \chi \) → \( \mu_3 \)
Winglet Parameterization

Closure of winglet surface by multisection extrusion between \( \{\mu, \lambda\} \) → winglet surface \( \kappa \)

**Leading edge**
Blade bends towards the suction side

**Trailing edge**
Blade bends towards the pressure side
Winglet Parameterization

Closure of winglet surface by multisection extrusion between \( \{\mu, \lambda\} \) → winglet surface \( \kappa \)

Leading edge
Blade bends towards the suction side

Trailing edge
Blade bends towards the pressure side

"Conic Winglet Design"
Radius of curvature varies along the winglet spine
Outline

1 Variable Blade Loading
2 Winglet
3 Turbulator
4 Numerical Model
5 Experimental Setup
6 Results
Turbulator Parameterization

PURPOSE OF THE TURBULATOR: avoid flow separation along blade

Adverse effects of flow separation in axial fans:
• Increased generation of noise
• Reduced cross sectional area of the flow channel → degradation of performance
Turbulator Parameterization

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Adverse effects of flow separation in axial fans:
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General usage of turbulators:
• Turn laminar flow into turbulent flow (near the leading edge)
• Increase the energy of an already turbulent boundary layer → move the point of flow separation further downstream (e.g. ailerons of commercial airliners)
Turbulator Parameterization

DEFINITION OF THE TURBULATOR GEOMETRY

Turbulator spine = parallel curve to the line of flow separation (offset $\gamma$)
Turbulator cross section = simple step (height $\tau$)
Turbulator Parameterization

DETERMINATION OF THE LINE OF FLOW SEPARATION

• either by integral convolution of the velocity field, or
• by showing the streamlines for the elements adjacent to the blade
Turbulator Parameterization

TURBULATOR AND RAPID PROTOTYPING
Machine: EOS 390 (selective laser sintering of polyamide)
For the turbulator to work properly, sharp edges are required

Note:
The final product is created by injection die molding (which can easily represent sharp edges).

Fine details of turbulator not sufficiently resolved → augmentation of optimization process with numerical tools necessary!
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<th>2 Winglet</th>
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<td>3 Turbulator</td>
<td>4 Numerical Model</td>
<td></td>
</tr>
<tr>
<td>5 Experimental Setup</td>
<td>6 Results</td>
<td></td>
</tr>
</tbody>
</table>
Numerical Model

Aerodynamic analysis

STAR-CCM+ 8.02
RANS solver
$k$-$\varepsilon$-turbulence model
All $y+$ wall model
Discretization of 1/7th of the model
(rotational symmetry)

Aeroacoustic analysis

STAR-CCM+ 8.02
LES solver
WALE subgrid scale
Discretization of the complete model
Numerical Model

Evolutionary Optimization

- Parametric geometry generation in the 3D-Modeler of STAR-CCM+
- Restore an identical operating point throughout the optimization (change rpm accordingly)
- Objective function evaluation
- Differential Evolution via Multi-Objective Genetic Algorithm NSGA-II (Non Dominated Sorting GA)
- Assisted by a metamodel to reduce the number of objective function evaluations
- Pareto front shows the best possible compromise between noise and efficiency over the selected design space
Numerical Model
Evolutionary Optimization

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**Discretization**

- Polyhedral discretization
- Prismatic expansion layer to resolve boundary layer
Numerical Model

Evolutionary Optimization

- Parametric geometry generation in the 3D-Modeler of STAR-CCM+
- Evaluation of objective functions is numerically expensive → Metamodell necessary!
  - Polynomial Response Surface Model (PRSM)
  - Artificial Neural Network (ANN)
  - Radial basis function network (RBF)
  - Kriging

Due to nonlinearity of the problem, PRSM was unsuitable.

Here we have chosen RBF.
Numerical Model

Evolutionary Optimization

- Parametric geometry generation in the 3D-Modeler of Star-CCM+
- Restore an identical operating point throughout the optimization (change rpm accordingly)
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Numerical Model

Evolutionary Optimization

OBJECTIVE FUNCTIONS

Aerodynamic Efficiency

\[ f_1 = \max \left( \frac{\Delta p \dot{V}}{M \omega} \right) \]

This allows to selectively minimize individual bands of the acoustic spectrum.

Soundpressure

\[ f_2 = \min \left( 10 \log \sum_{i=1}^{r} 10^{(L_p)_i - (L_A)_i} \right) \]

Sound pressure of frequency band with index \( i \)

A-weighting associated with frequency band of index \( i \)

Here we choose to minimize the tonal noise at BPF\(_1\)=840 Hz and BPF\(_2\)=1680 Hz
Outline

1. Variable Blade Loading
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5. Experimental Setup
6. Results
Experimental Setup

Physical prototype
Experimental Setup

Physical prototype

Aerodynamic test rig

Acoustic test rig

Inlet nozzle

Impeller

Guide vanes

Casing
Results

Downstream flow field
Q-Criterion = 2e+5

Time step: 5e-5 s
n=7200 min⁻¹
Results

Pareto front
Results

Averaged swirl velocity $r\bar{c}_u$ at trailing edge.

Pareto front

- SHROUD
- HUB
Results

Pareto front

Averaged swirl velocity $r\bar{c}_u$ at trailing edge
Results

Pareto front

Averaged swirl velocity $\overline{rC_u}$ at trailing edge
Results

Pareto front

Averaged swirl velocity $r\overline{c_u}$ at trailing edge
**Results**

**Pareto front**

Averaged swirl velocity $rar{c_u}$ at trailing edge

**Conclusions**

- For high efficiency, all blades are loaded equally
- For low tonal noise, all blades are loaded differently
Results

Typical sound pressure frequency spectrum for a sensor in the Large Eddy Simulation
### Results

Comparison between

- (a) physical test
- (b) simulation

<table>
<thead>
<tr>
<th>Frequency [Hz]</th>
<th>Physical Test</th>
<th>Simulation Star-CCM+ (LES)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>65</td>
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<tr>
<td>125</td>
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<td>94</td>
</tr>
<tr>
<td>16000</td>
<td>96</td>
<td>96</td>
</tr>
</tbody>
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- **BPF\(_1\) = 840 Hz**  
- **BPF\(_2\) = 1680 Hz**
Results

Comparison between (a) physical test and (b) simulation

Rotational frequency:
RF = 7200 rpm / 60 = 120 Hz

Source: Eccentricity of the physical specimen (absent in numerical simulation)

Represents an advantage, since the spectrum is not polluted by spurious noise.
Results

Comparison between (a) identical blade geometry (physical tests) and (b) varying blade geometry.
# Summary

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[Image of a 3D model of a fan with various colored sections]