
# AERODYNAMICS AND ACOUSTICS OF FANS

# - RECENT ADVANCES AND OPEN ISSUES -

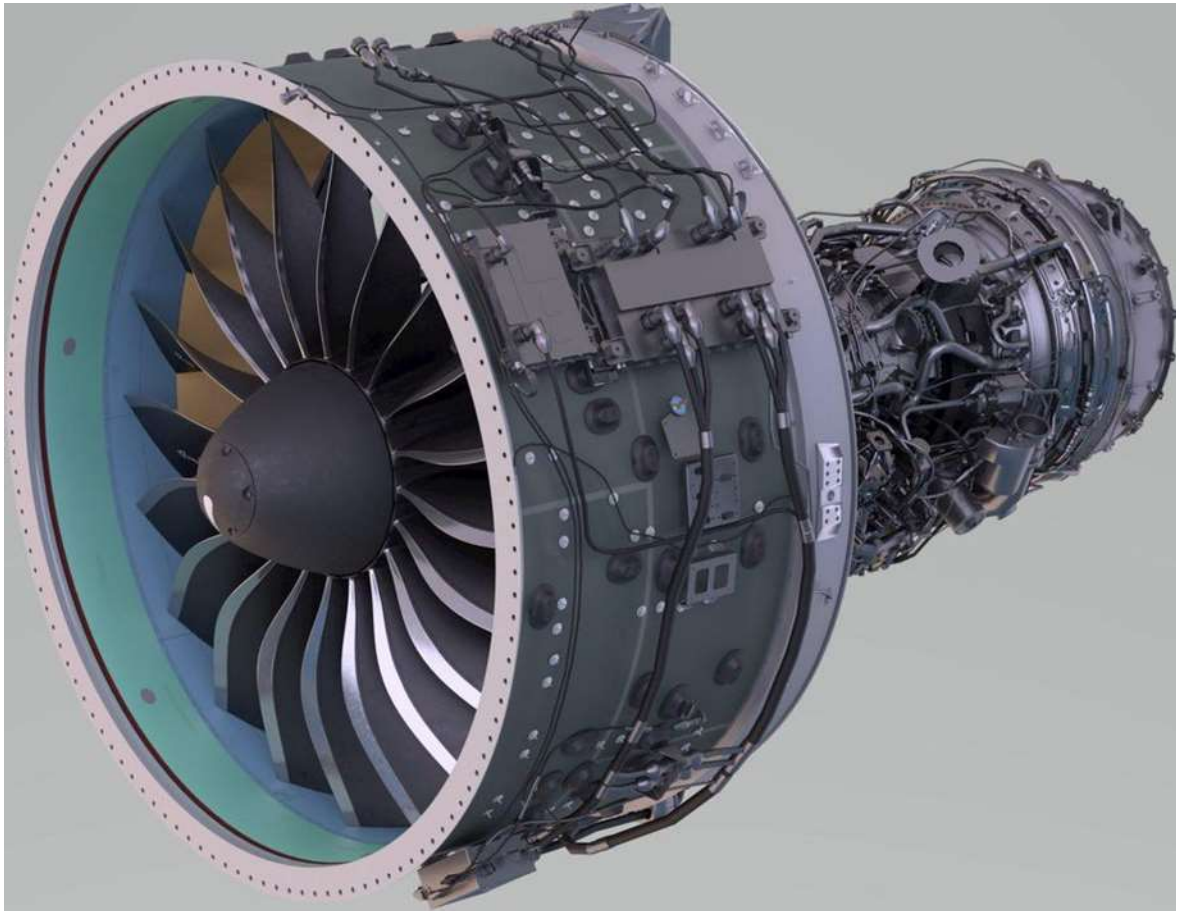
**Prof. Dr.-Ing. Th. Carolus**

**Steinbeis Transfer Center FLOWTRANS, Netphen, Germany**
**(formerly University of Siegen, Department Mechanical Engineering)**

Steinbeis-Transferzentrum FLOWTRANS


Boing 747-400
with Rolls-Royce RB211
1989

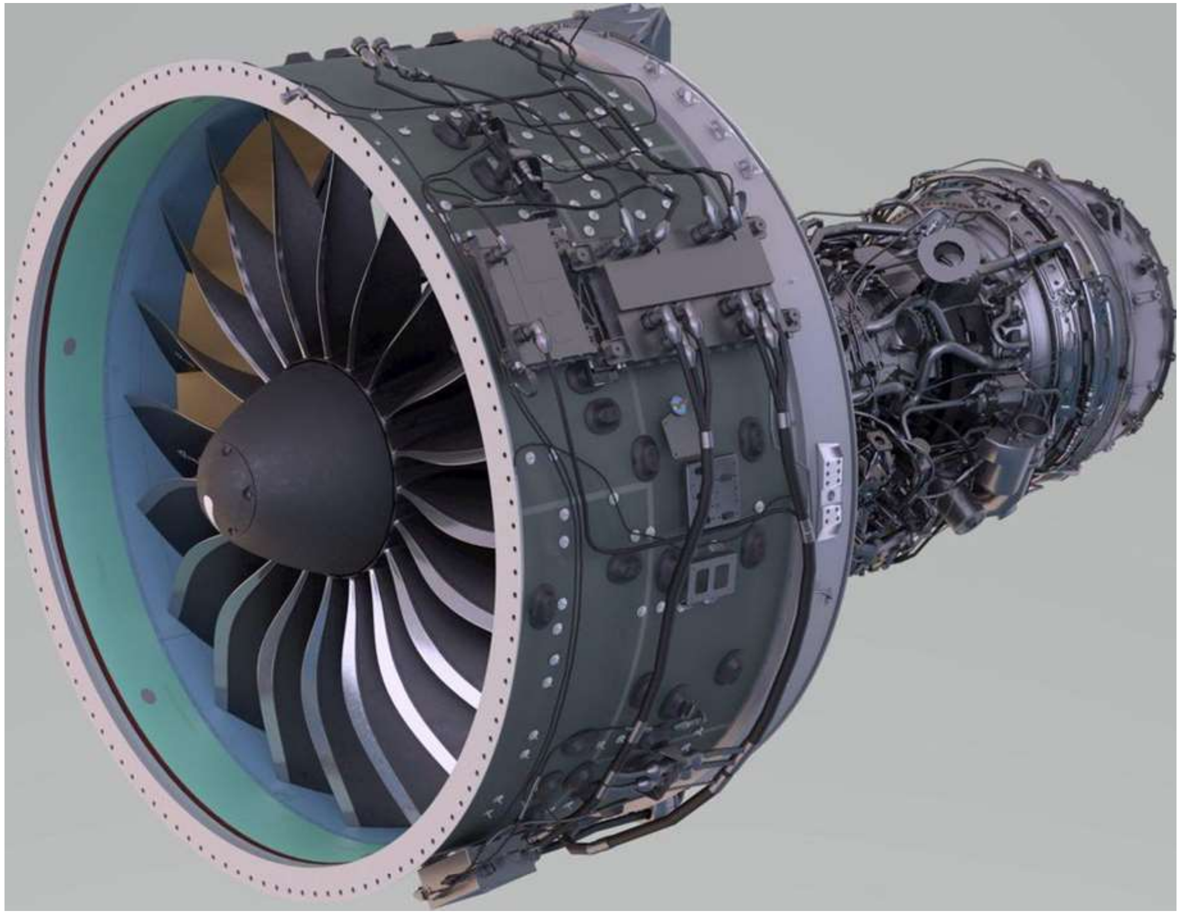
# Advanced Fan Design: Pratt & Whitney PW 1000G geared turbofan, 2016



*https://www.forbes.com, https://en.wikipedia.org/wiki/Pratt_%26_Whitney_PW1000G*

- 3:1 reduction gears for the fan → each engine element operates at optimal speed (4,000–5,000 rpm for the fan and 12,000–15,000 rpm for the spool, the high-pressure spool spinning at more than 20,000 rpm)
- Increased efficiency and reduced noise
- E.g. for Airbus A320neo

# Advanced Fan Design: Pratt & Whitney PW 1000G geared turbofan, 2016



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- Increased **efficiency** and reduced **noise**
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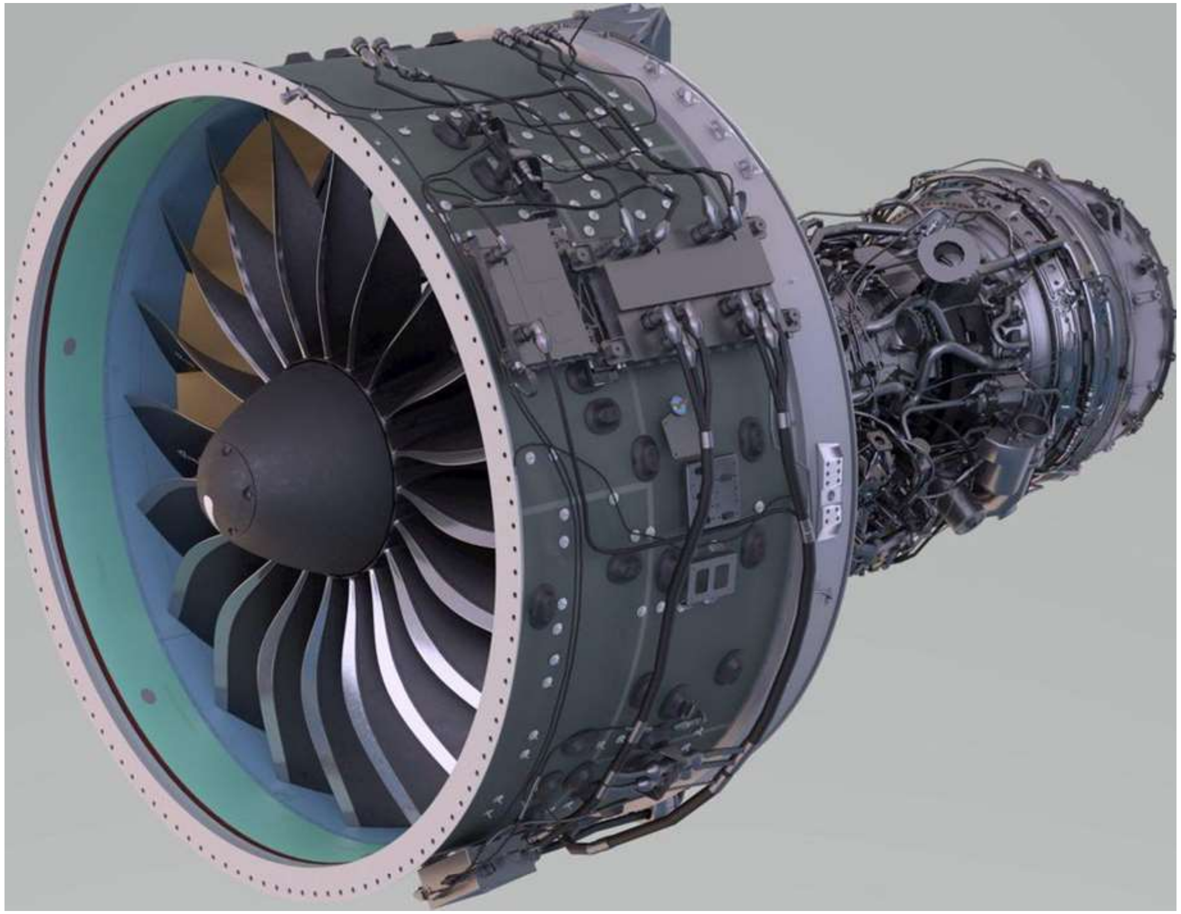
## Small table fans: Design by Peter Behrens, manufactured by AEG, 1908/1909

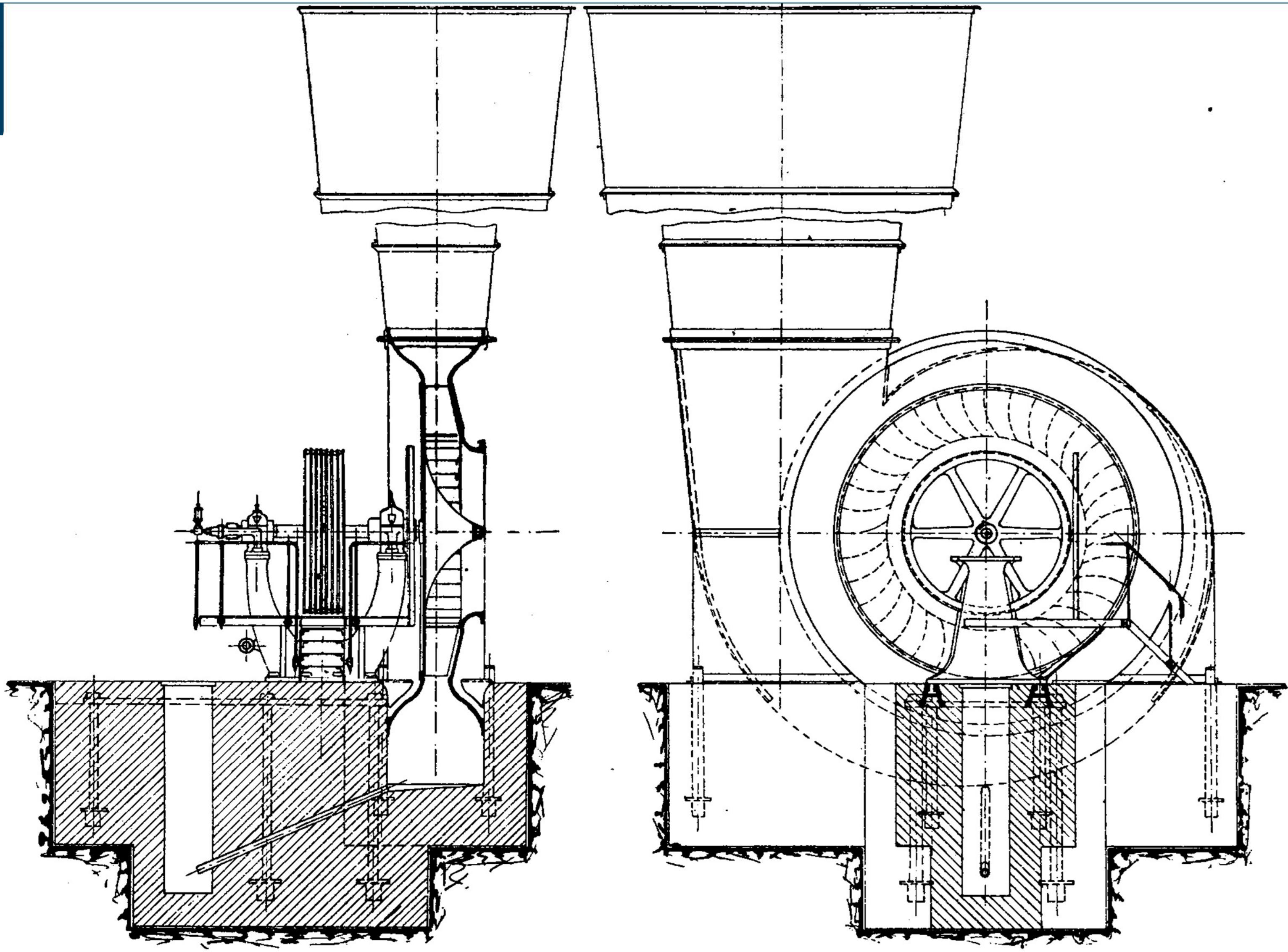
*Pinakothek der Moderne, München*

## From Jet Engine Fan to Diesel Engine Cooling Fan



*D. Arnold, Fa. Hägele, Schorndorf 2024*

## Pit fan, around 1900



*Maschinenfabrik Hohenzollern, Düsseldorf-Grafenberg*
*(from: Rudolf Vogdt: Pumpen, Hydraulische und pneumatische Anlagen, G. J. Göschen'sche Verlagshandlung 1906)*

# Part 1:

# Numerical flow simulation as the third pillar of (fan) aerodynamics

## Classification of flow simulation methods relevant for industrial application

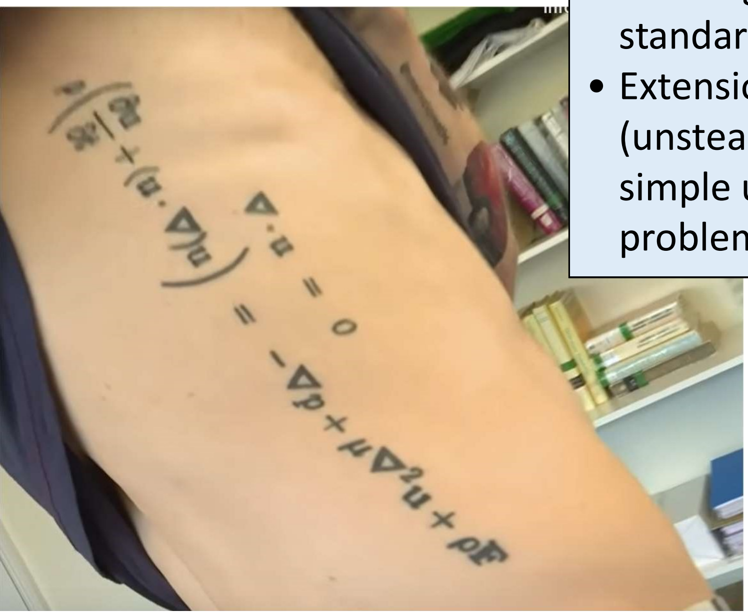
**Class I**
**RANS**
**Reynolds-averaged Navier-Stokes-Simulation**

- Solves the Reynolds-averaged Navier-Stokes-equations, turbulence not resolved, modeled
- Working hoarse for standard tasks
- Extension: URANS (unsteady RANS) for simple unsteady problems

**Class II**
**LES**
**Large Eddy Simulation**

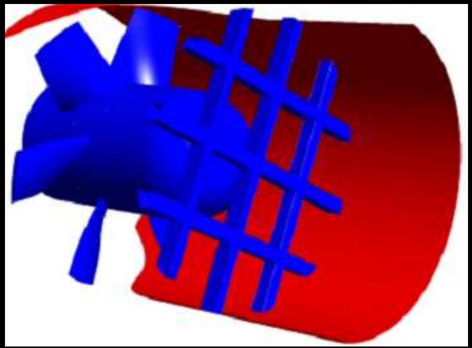
- Coarse structures in the flow field (large eddies) are resolved in space and time
- Only fine structures are modeled
- Good for unsteady problems
- May yield input for acoustics

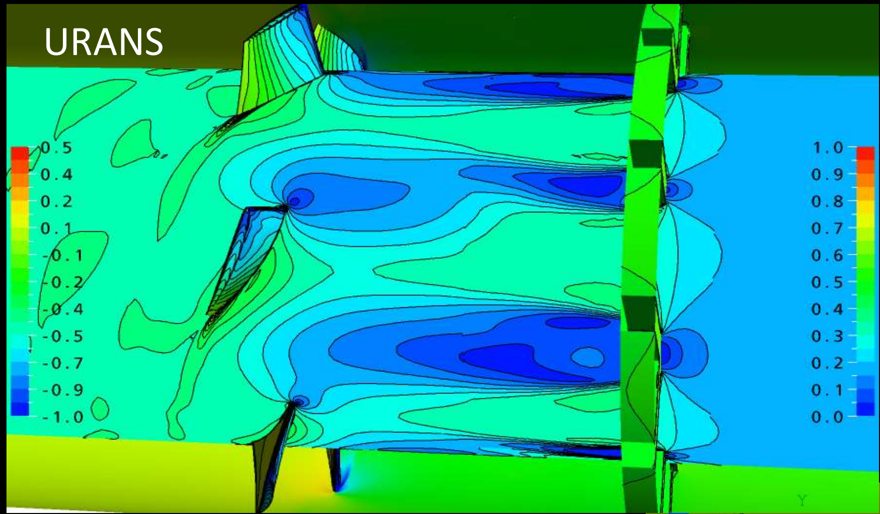
Performance curves
Details of flow field
(Sound field)

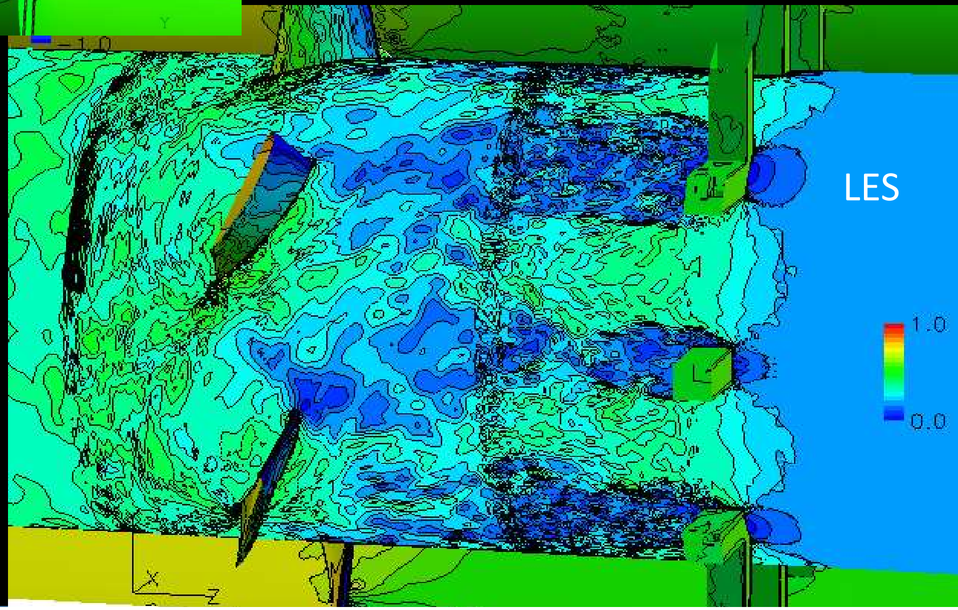


Navier-Stokes Equations - Numberphile
YouTube · Numberphile · 27 Aug 2019

## Comparison: RANS- and LES-predicted flow field






*H. Reese, University Siegen and University Tokio, 2007*

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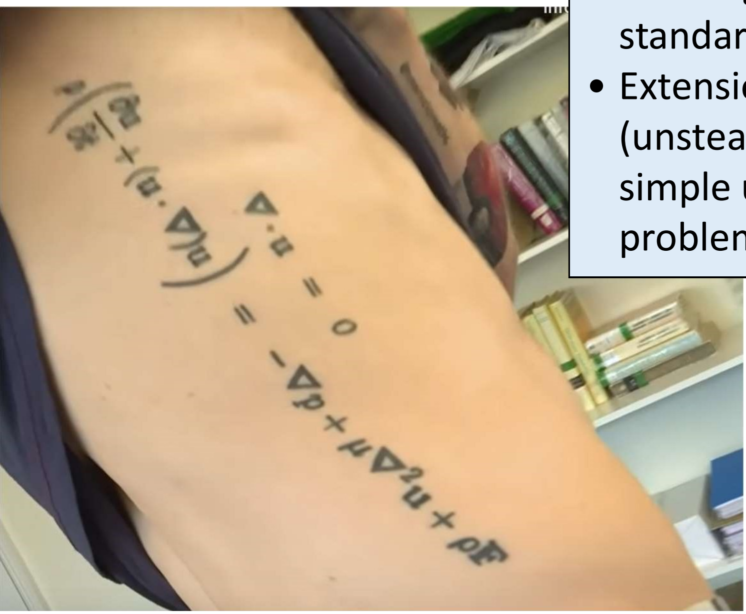
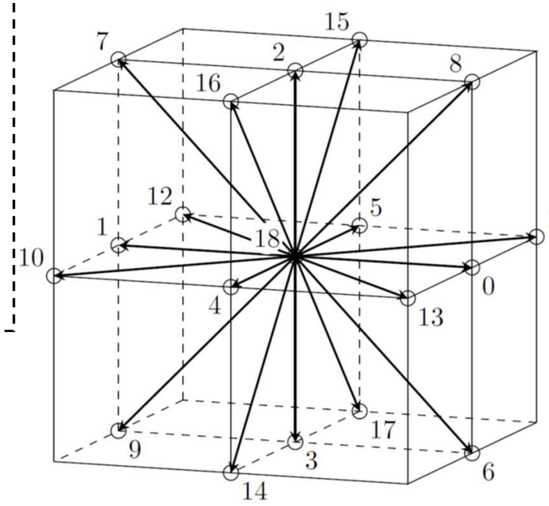
**<u>Class III</u>**
**LBM**
**Lattice-Boltzmann Method**
(see next slide)

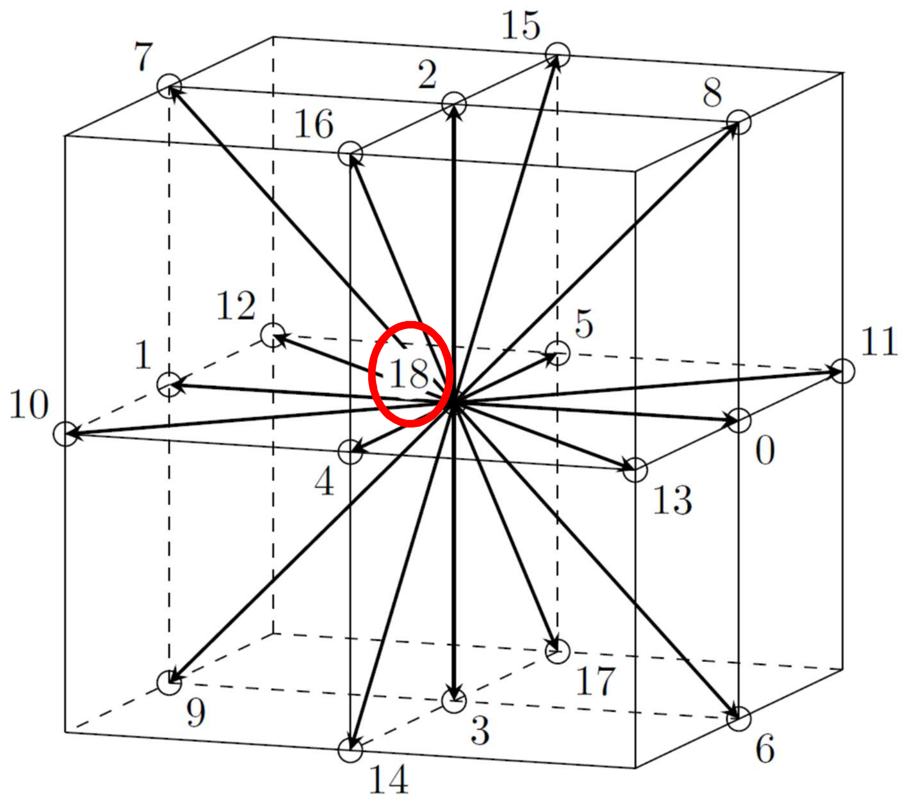
Performance curves
Details of flow field
(Sound field)



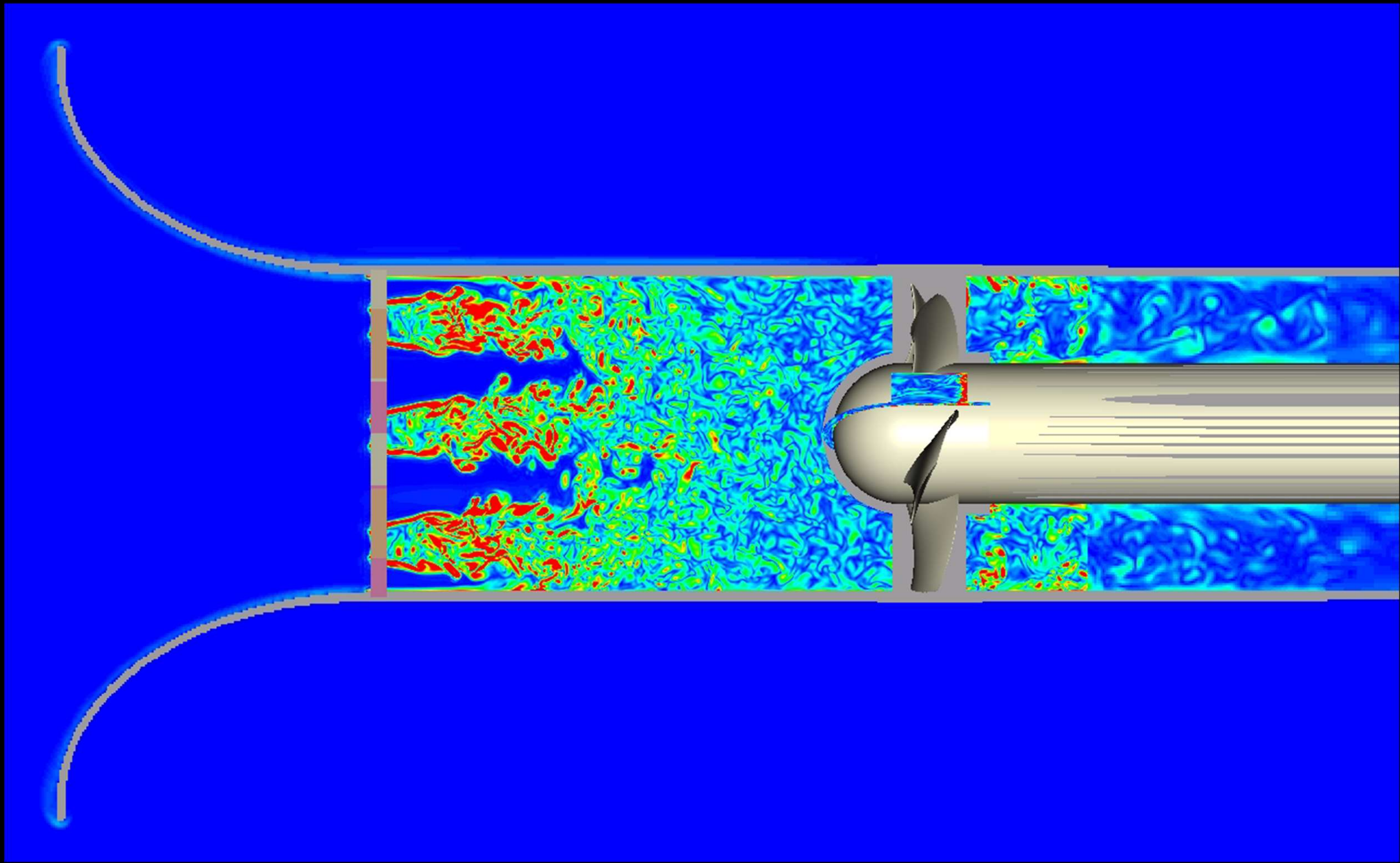



**“BOTTOM-UP”**
**Solving "mesoscopic" Boltzmann equation to predict macroscopic fluid dynamics**

- **Particle movement and collisions with particle distribution functions (PDF).**
- **From PDFs the macroscopic hydrodynamic quantities are obtained.**
- **Naturally transient and for compressible fluids**
- **Very large eddy simulation (VLES) turbulence modelling.**
- **Resolves unsteady turbulent flow field and sound field simultaneously**

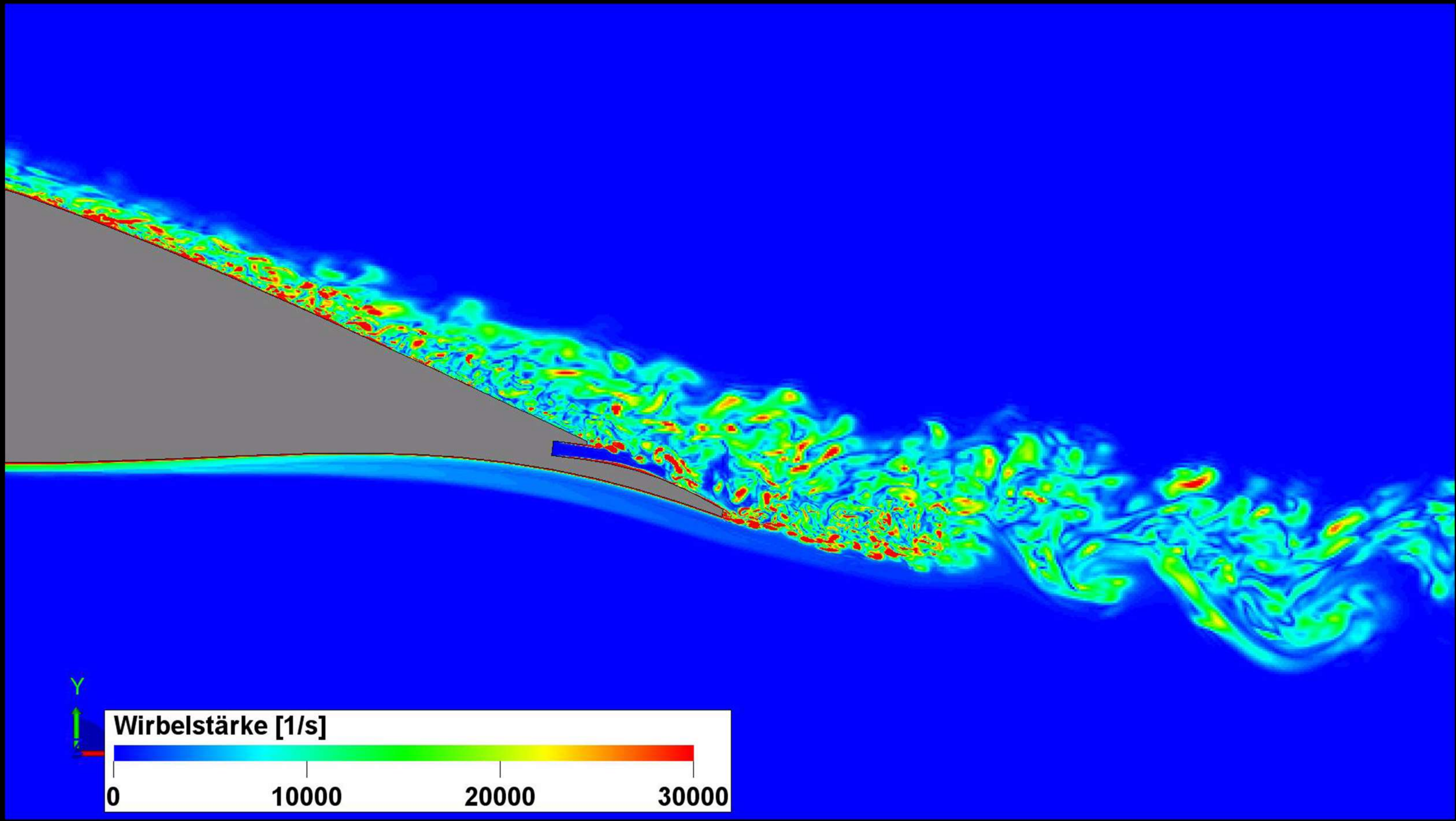


## LBM-predicted flow field: Three-dimensional, unsteady, fully turbulent



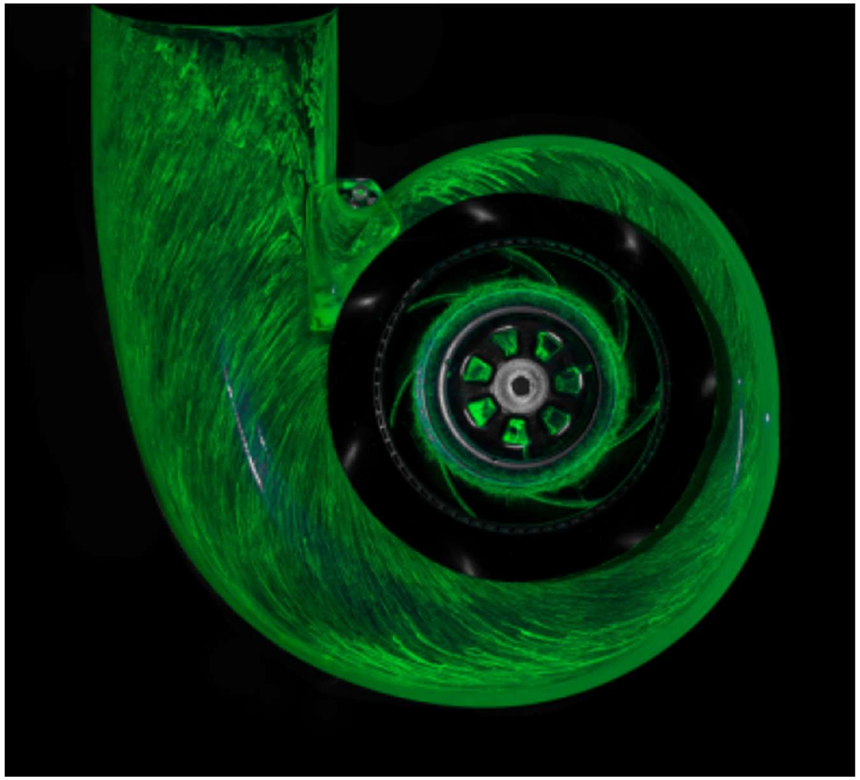
*T. Zhu, M. Sturm, University Siegen 2016*

LBM-predicted flow field in the vicinity of an airfoil trailing edge

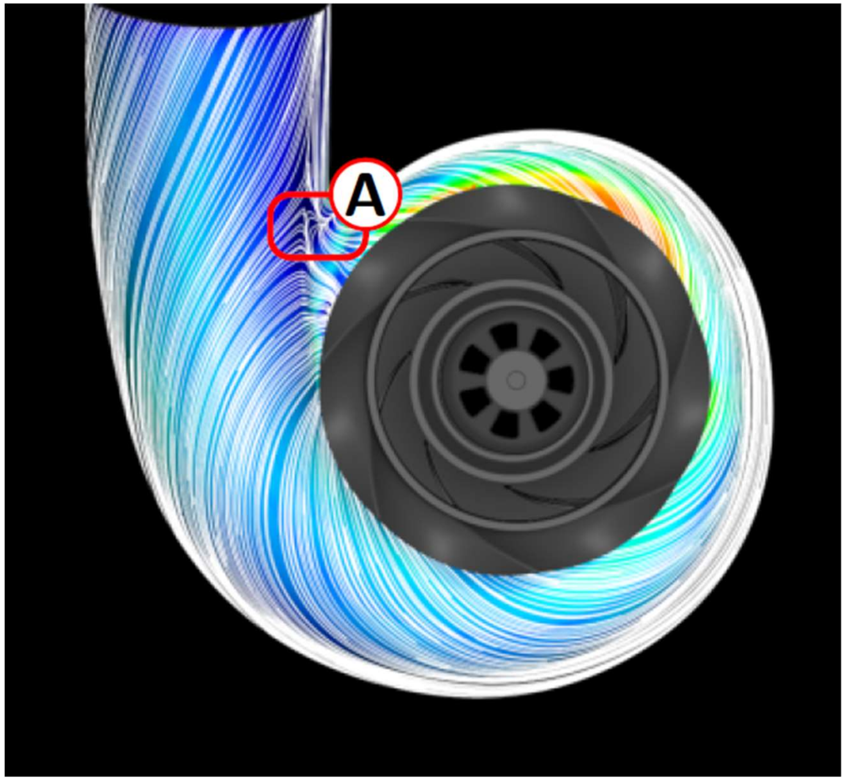



F. Manegar, University Siegen 2018

## Centrifugal fan



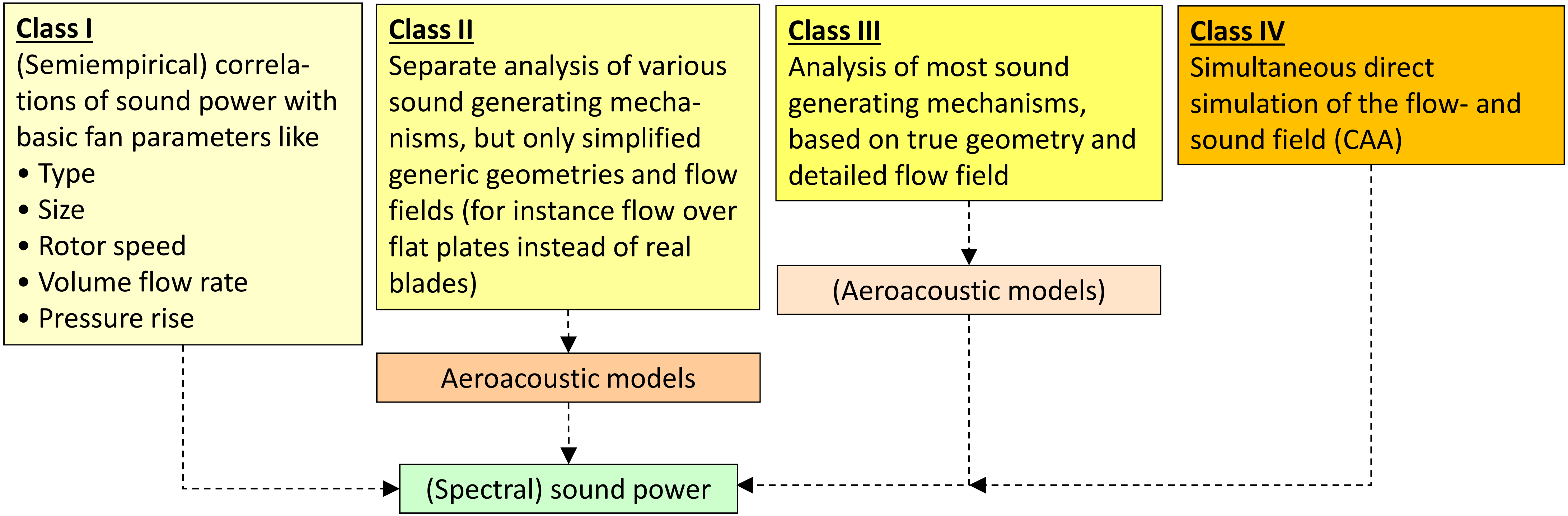
Streamlines from experimental oil paint method



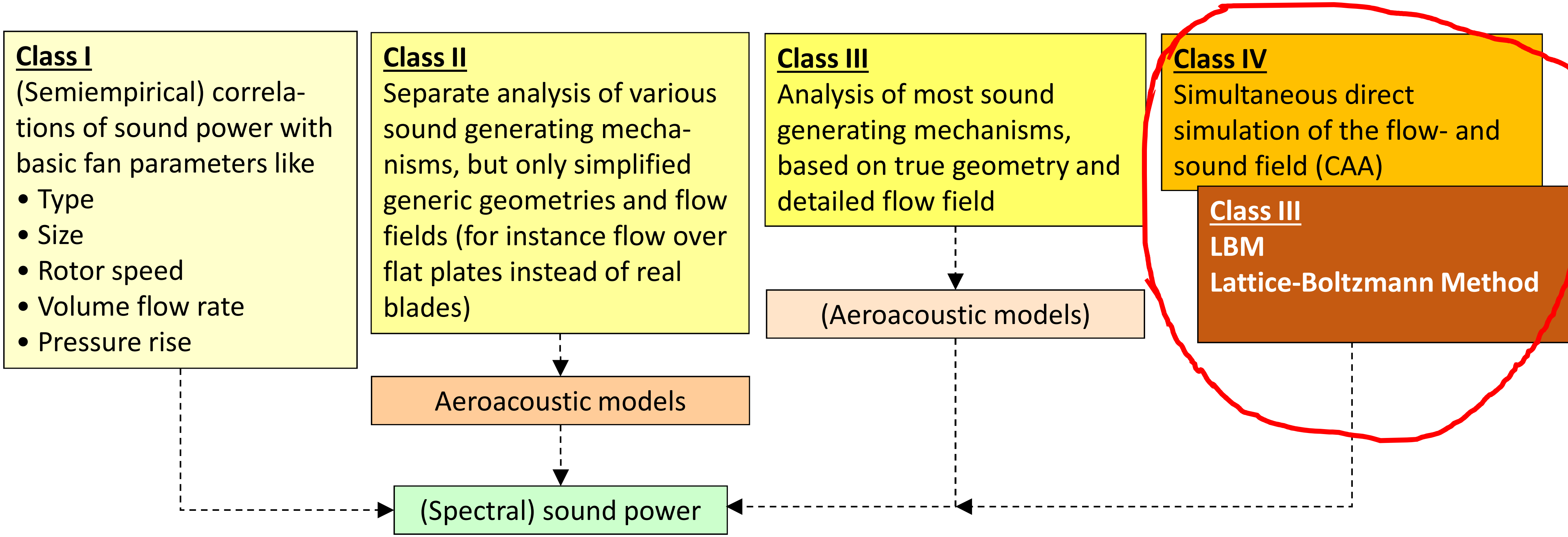

from LBM

*R. Schäfer, Technischen Universität Kaiserslautern, 2021*

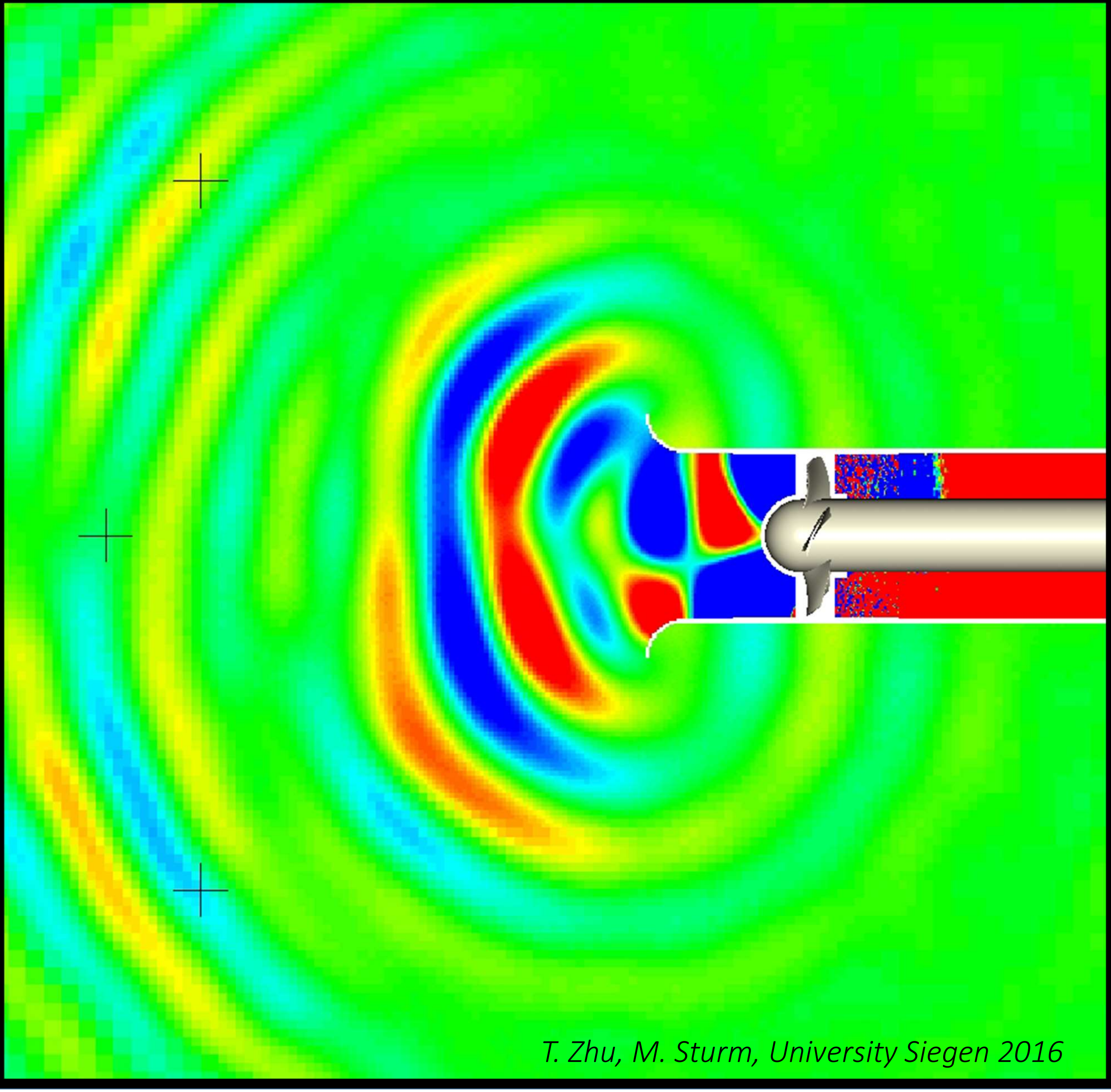
# Classification of sound prediction methods



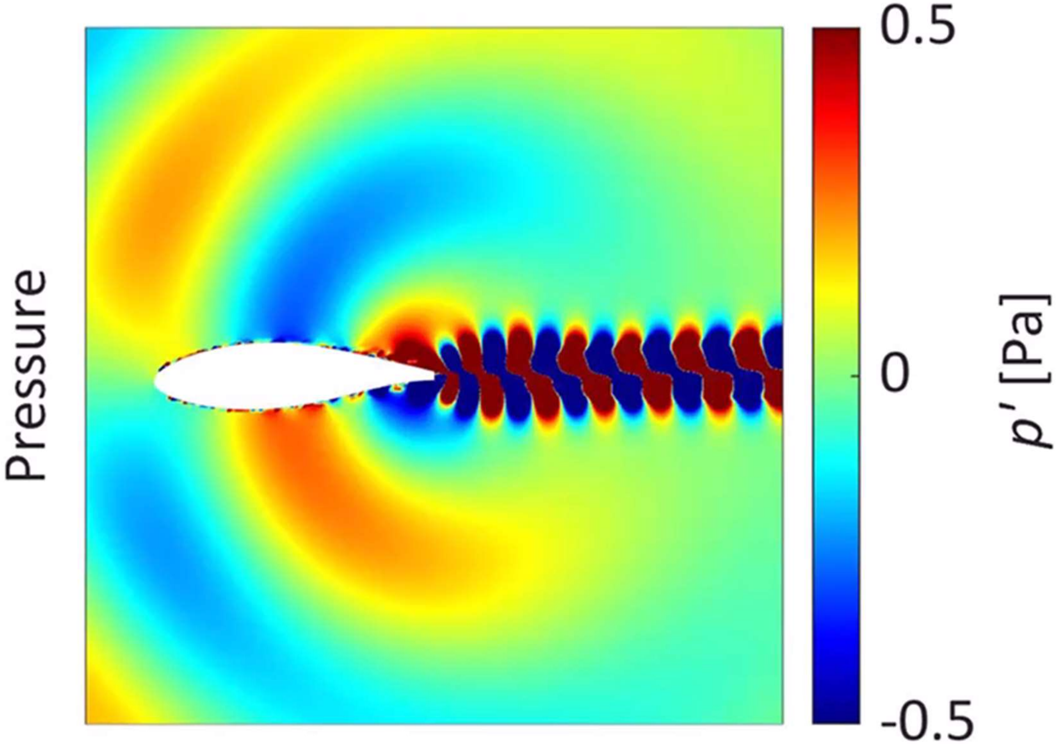
# Classification of sound prediction methods

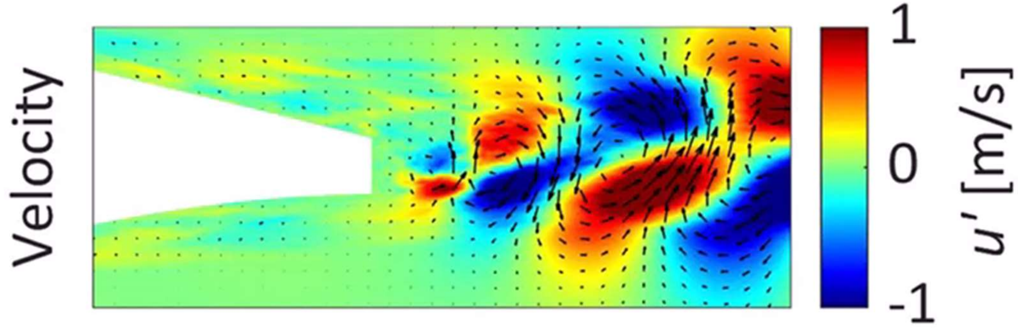


**LBM-predicted flow-induced sound field**



**LBM-predicted tonal sound from a blunt airfoil trailing edge**



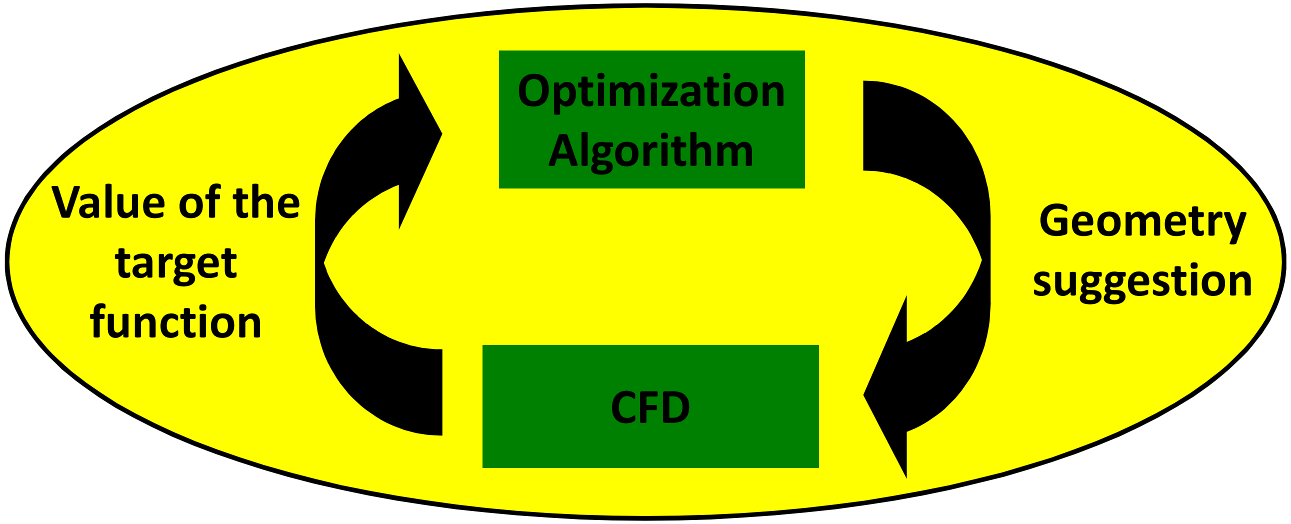

*K. Stahl, École de Technologie Supérieure Montreal and University Siegen 2023*


SIMULIA
NREL/SANDIA 5MW/61.5m Wind Turbine Reference Model using PowerFLOW

# Part 2:

# CFD-based optimization

## Option 1: CFD in the optimization loop

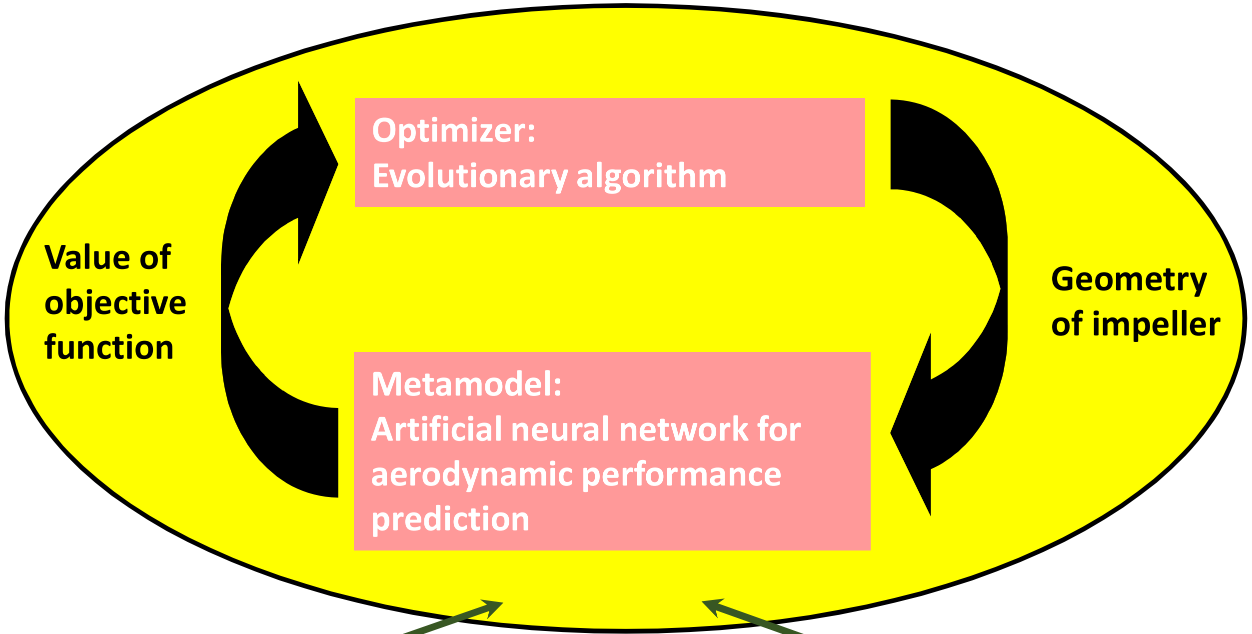


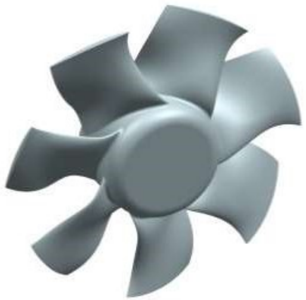

### Drawbacks

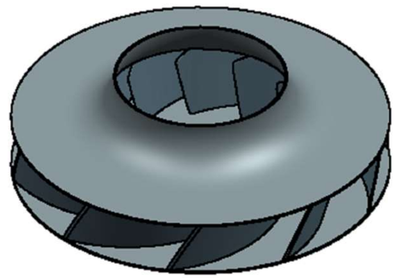
- time consuming
- license cost
- automating the meshing, solving and evaluation is a challenge

→ **alternative solution: replace CFD with CFD-trained metamodels**

# Option 2: CFD for generation of training data for a metamodel



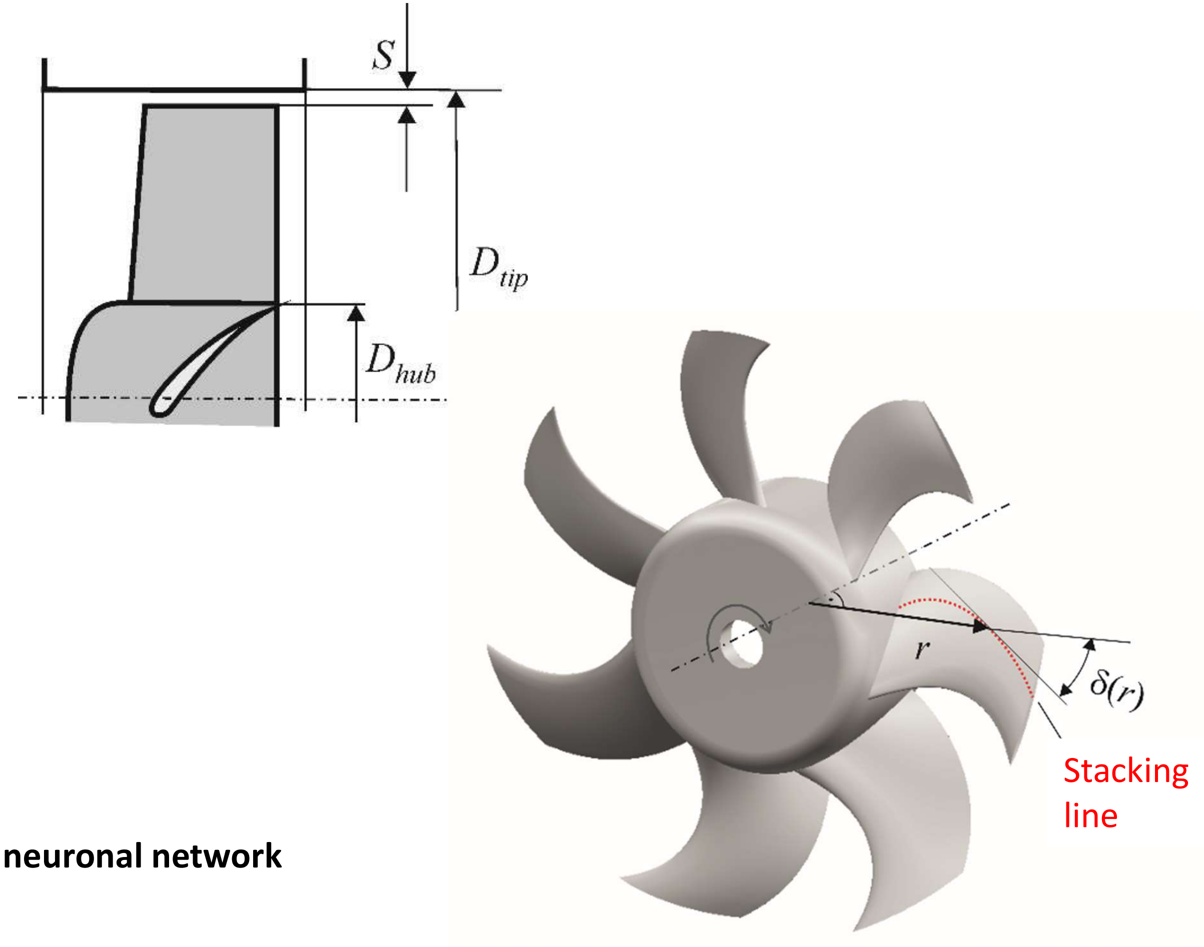


Example 1: Training data from CFD performance prediction of 14,000 axial fan impellers (= individuals)

Example 2: Training data: CFD performance prediction from 4,000 impellers (= individuals)

# Example 1: Axial fan optimization - Geometric parameters varied

| Parameter | | Range |
|---|---|---|
| Hub-to-tip ratio | $\nu$ | 0.3 - 0.7 |
| Number of blades | $z$ | 5 - 11 |
| Chord-length ratio | $c/D_{tip}$ | 0.13 - 0.33 |
| Blade sweep angle | $\delta$ | -60° - +60° |
| ..... | ..... | ...... |

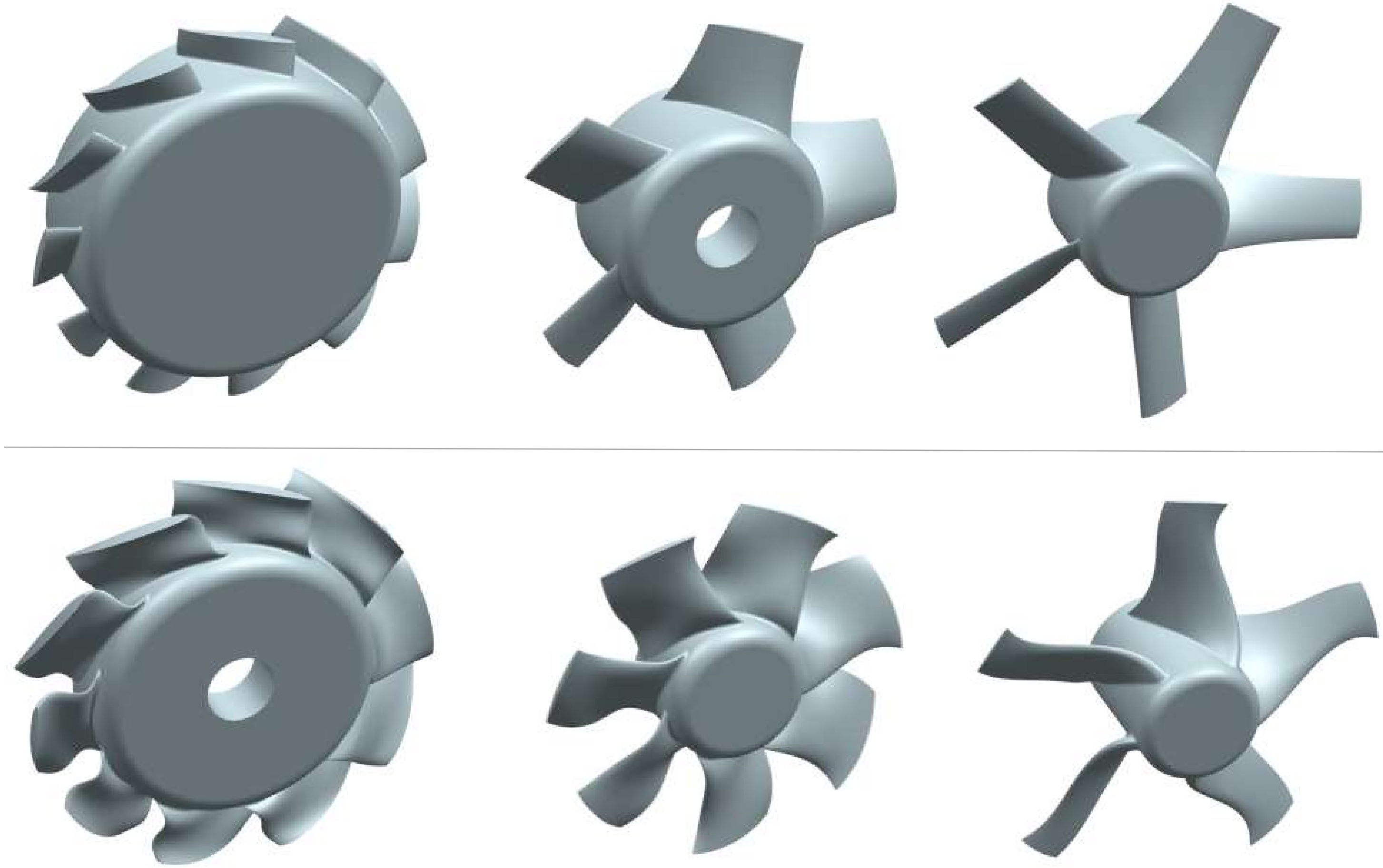



- Parameter variation by an optimized Latin Hypercube
- Automized and optimized CFD set up (RANS)
- Removing of non-phyical CFD results
- Selection of suitable metamodel types; here artificial neuronal network

# Classic vs. neuronal-network based design

Classic design

Optimization-based design



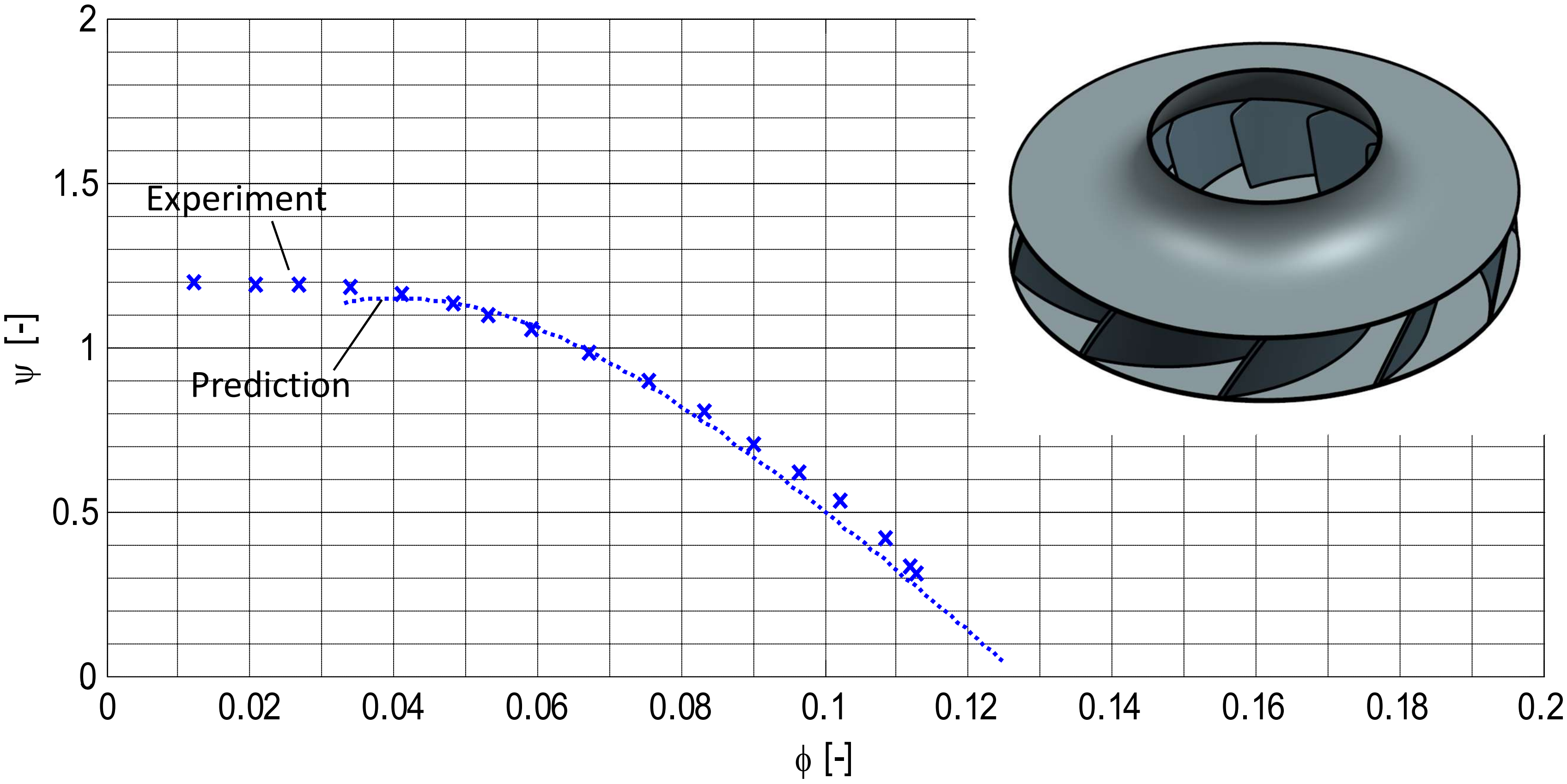
$\Delta\eta_{ts}$= +14% points

+4% points

+2% points

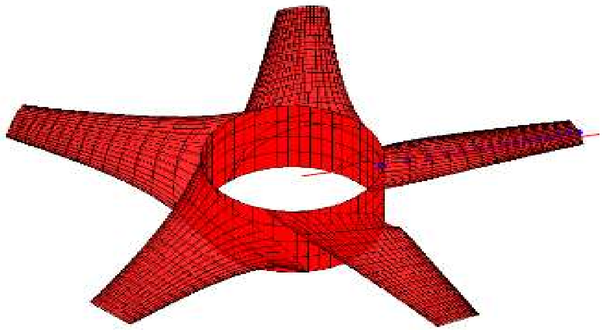
*K. Bamberger, University Siegen 2015*

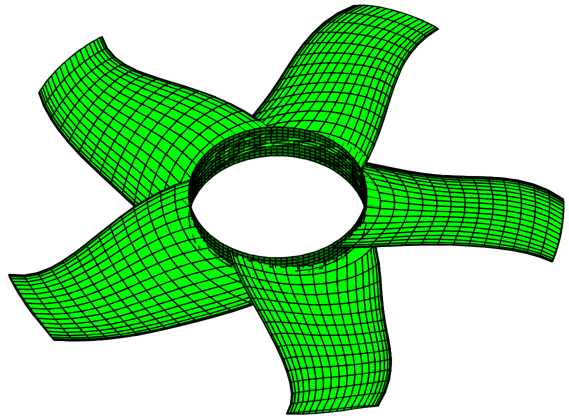
# Example 2: Centrifugal fan optimization - Experimental vs. neuronal-network based predicted performance



# Final remark and references (I)

- The scheme presented is based on a data-driven model.
- It relies on training data collected somewhere and hence does not yield the physical reason for any of its results.
- The training data had been generated beforehand by CFD.
- Since CFD is still costly, the training data is not very *big* data.
- Naturally, the scheme is limited to a class of machines with certain geometric design features, the training data had been generated for; e.g. centrifugal impellers with 2D simple curved blades and a defined range of parameter values
- But: Within the range of the parameters used for generating the training data all combinations of parameter values are possible $\Rightarrow$ Fast and surprising results!





## Final remark and references (II)


Bamberger, K., Carolus, T.: Development, Application,and Validation of a Quick Optimization Method for the Class of Axial Fans. ASME J. of Turbomachinery, Nov 2017, Vol. 139

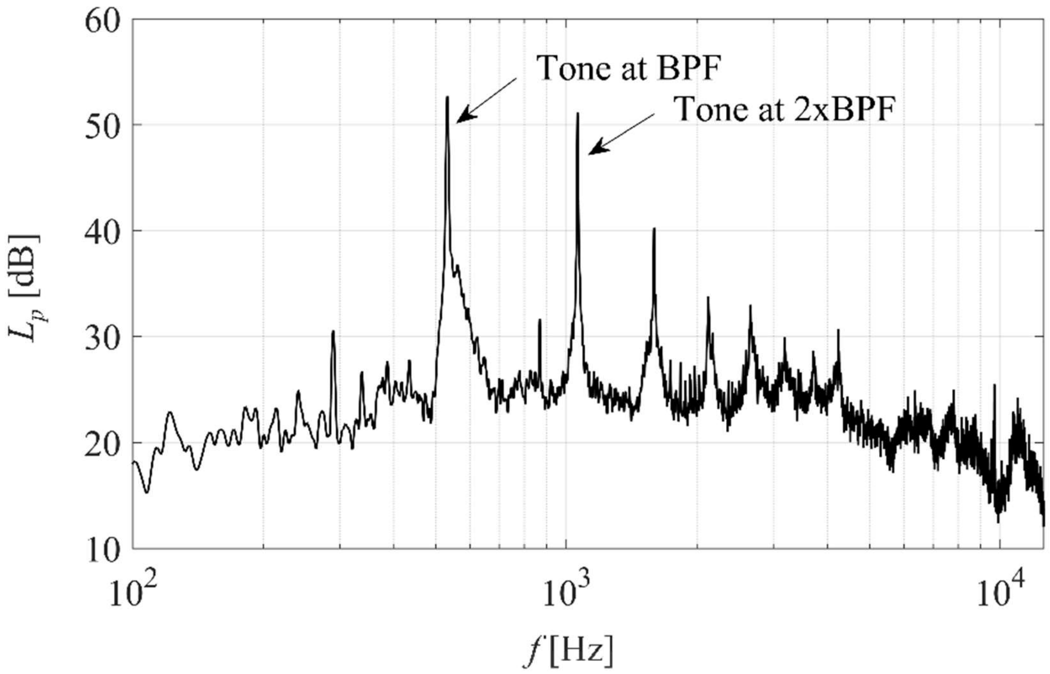
Bamberger, K., Carolus, T., Belz, J., Nelles, O.: Development, Validation, and Application of an Optimization Scheme for Impellers of Centrifugal Fans Using Computational Fluid Dynamics-Trained Metamodels. ASME J. of Turbomachinery, Nov. 2020, Vol. 142

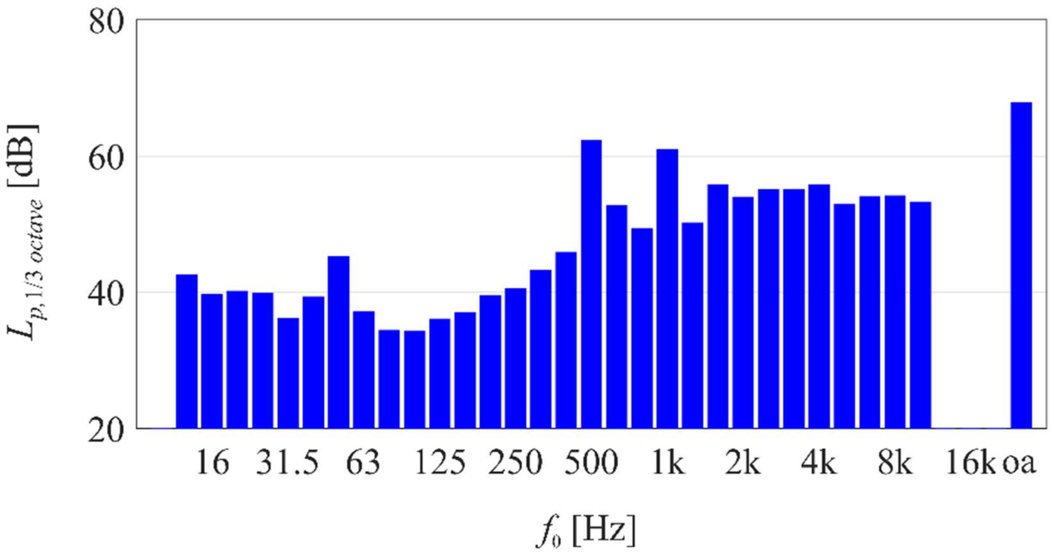

## Part 3:

## Quality of fan noise - Psychoacoustic methods

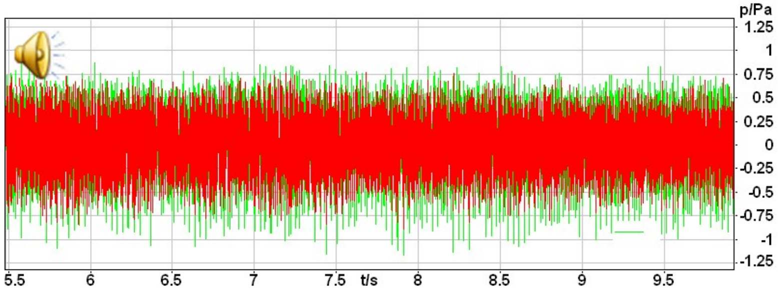
# Fan Noise

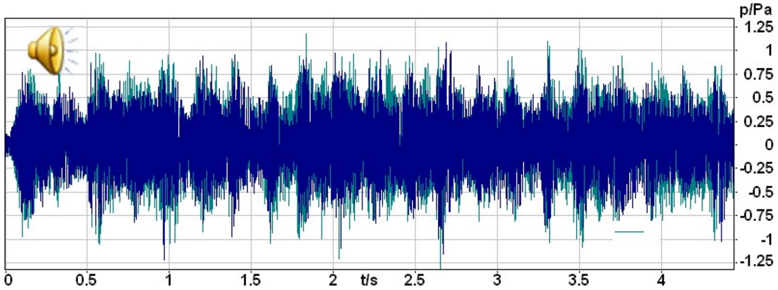

Mic

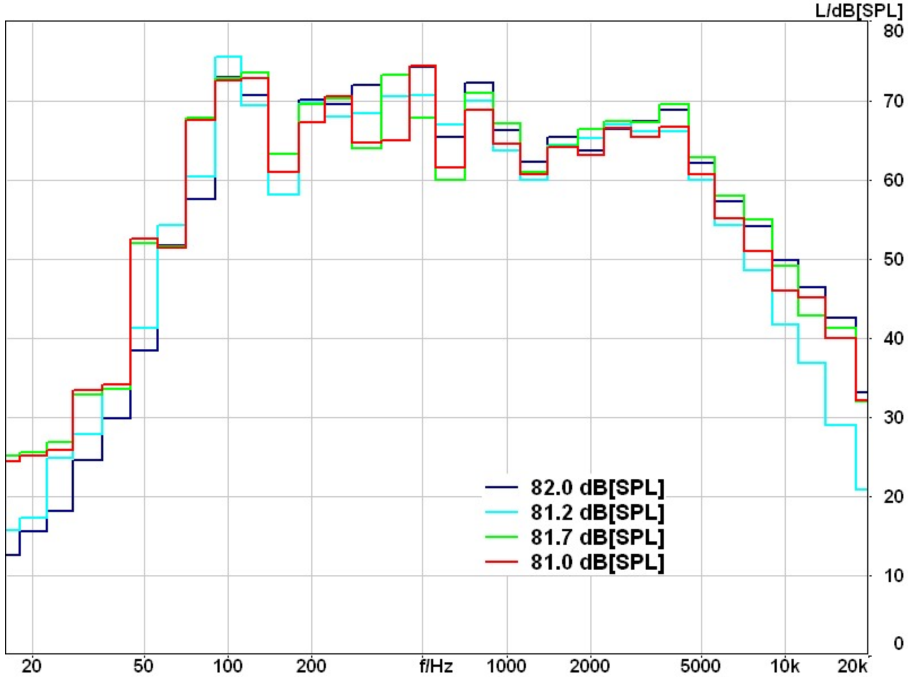

Tone at BPF
Tone at 2xBPF
$L_p$ [dB]
$f$ [Hz]
60
50
40
30
20
10
$10^2$
$10^3$
$10^4$


$L_{p,1/3\ octave}$ [dB]
$f_0$ [Hz]
80
60
40
20
16
31.5
63
125
250
500
1k
2k
4k
8k
16k
oa

# Which sound is more pleasant?




K. Genuit, HEAD, „Subjektive“ Beurteilung und „objektive“ Analyse, ebm Innovationsforum 2013

# Sound quality

- It is well-known that the overall level and even the spectrum do not fully reflect the perception of fan noise by humans.

- The effect of sounds on humans can be viewed either from the perspective of annoyance

  or

  in terms of a *product sound quality*, defined as the adequacy of a sound in relation to the product, BLAUERT and JEKOSCH 1997.

# How to predict sound quality

Subjective testing of sounds by jury tests

*Statistical regression for relating subjective response to objective metrics*

Compute objective psychoacoustic metrics of sounds (loudness, sharpness, roughness, ...)

$$\text{Quality} = \sum_j k_j \,(j \text{ objective psychoacoustic metrics})$$

*C. Feldmann, University Siegen 2018*

## Jury tests

- Jury test A: Participants are asked to describe a class of sounds (or sound sources, e.g. vacuum cleaners) via adjective scales.
- Jury test B: Participants are asked to rate sounds with the target to rate their product related sound quality.

| No. | |
|---|---|
| 1 | completely disturbing - not disturbing at all |
| 2 | cannot be blanked out at all - can be blanked out completely |
| 3 | totally annoying - not annoying at all |
| 4 | unpleasant - pleasant |
| 5 | obtrusive - unobtrusive |
| 6 | completely humming - not humming at all |
| 7 | dark - light |
| 8 | completely roaring - not roaring at all |
| 9 | low - high |
| 10 | completely booming - not booming at all |
| 11 | heavy - light |
| 12 | completely fluctuating - not fluctuating at all |
| 13 | unsteady - steady |
| 14 | completely varying - not varying at all |
| 15 | moving - static |
| 16 | uneven - even |
| 17 | weak - strong |
| 18 | low performance - high performance |
| 19 | powerless - powerfull |
| 20 | completely hissing - not hissing at all |
| 21 | completely rustling - not rustling at all |
| 22 | completely whistling - not whistling at all |
| 23 | completely grinding - not grinding at all |

Collection of adjective scales for characterizing the noise of fans and air handling units. *(Feldmann 2019)*

## Psychoacoustic metrics

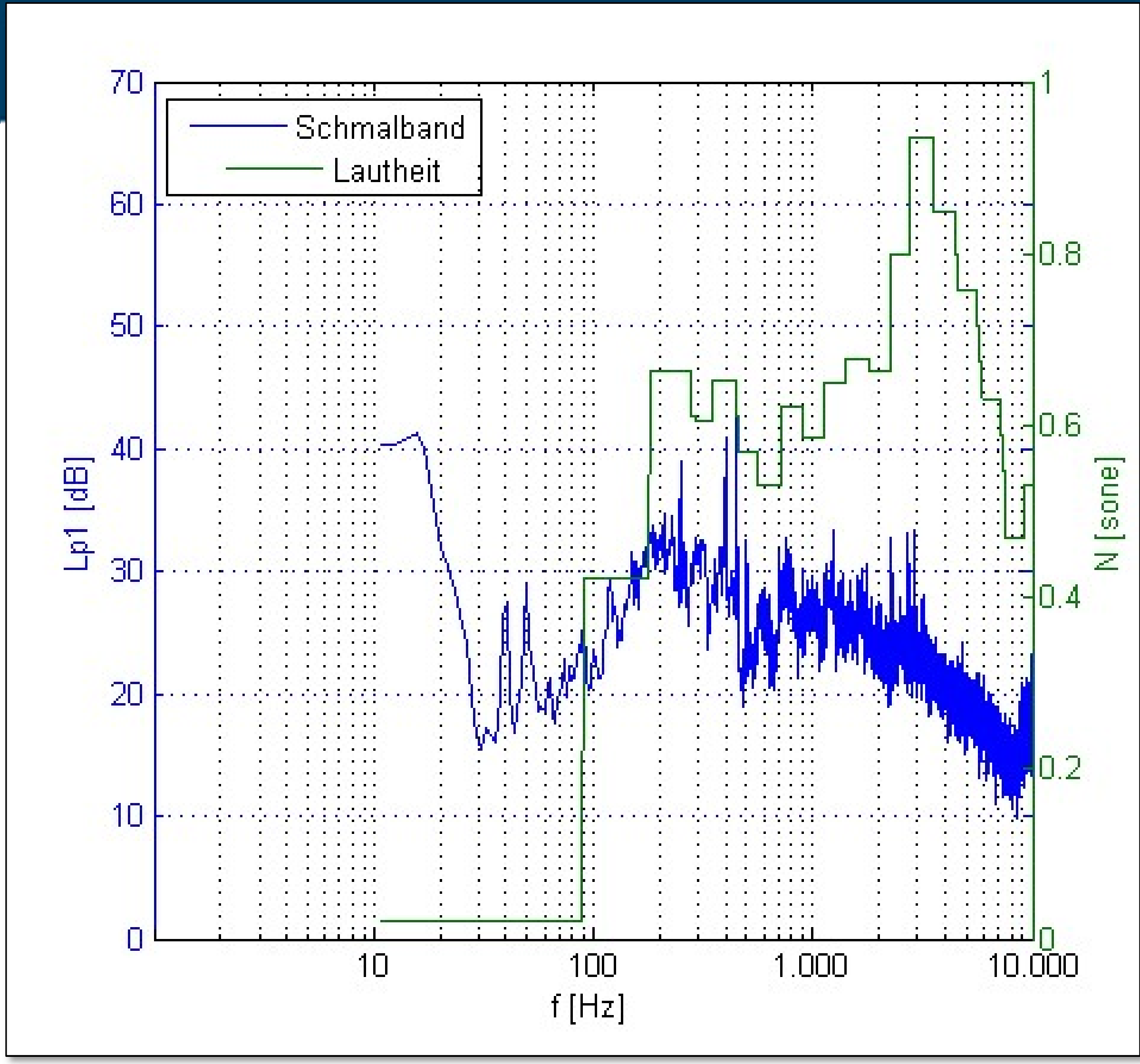
- In parallel, psychoacoustic metrics such as

  - loudness
  - sharpness
  - tonality
  - roughness, etc.

  are derived from the objectively measured acoustic signatures of the sounds.

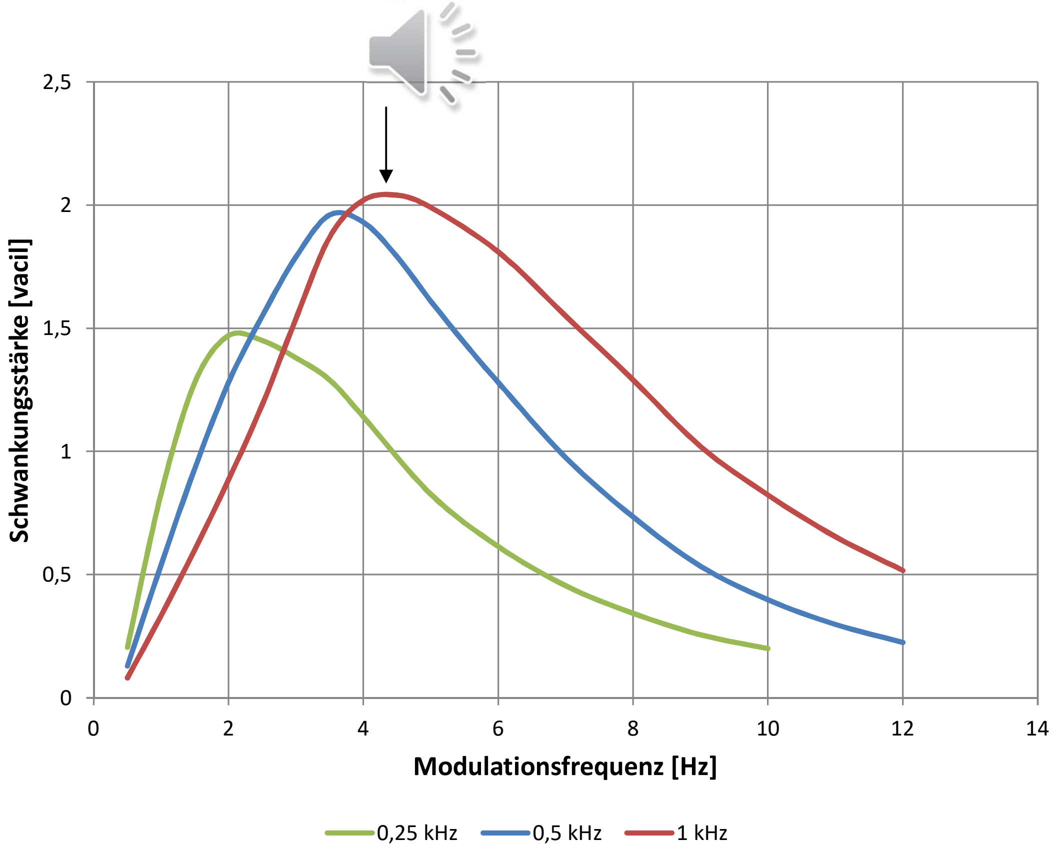
## Psychoacoustic metric PERCEIVED LOUDNESS

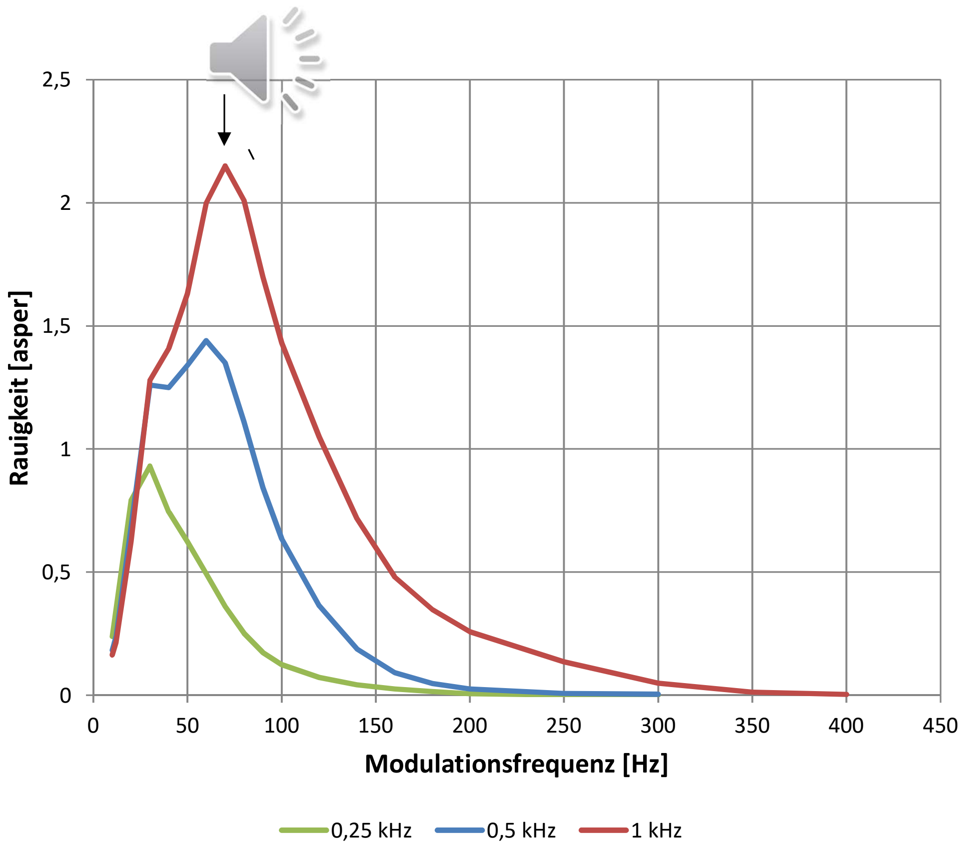
- Can be calculated from any narrow band spectrum.
- Standardized according to DIN 45631.
- 1 sone is assigned to a sinusoidal tone of 1 kHz with 40 dB(SPL) .



## Psychoacoustic metrics FLUCTUATION INTENSITY and ROUGHNESS

- Measure of the amplitude and frequency modulations present in the sound
- If modulation frequency is very low: fluctuation strength in [vacil], otherwise: roughness in [asper]
- Determinable e.g. with the software ArtemiS Suite 5.1 from Head Acoustics



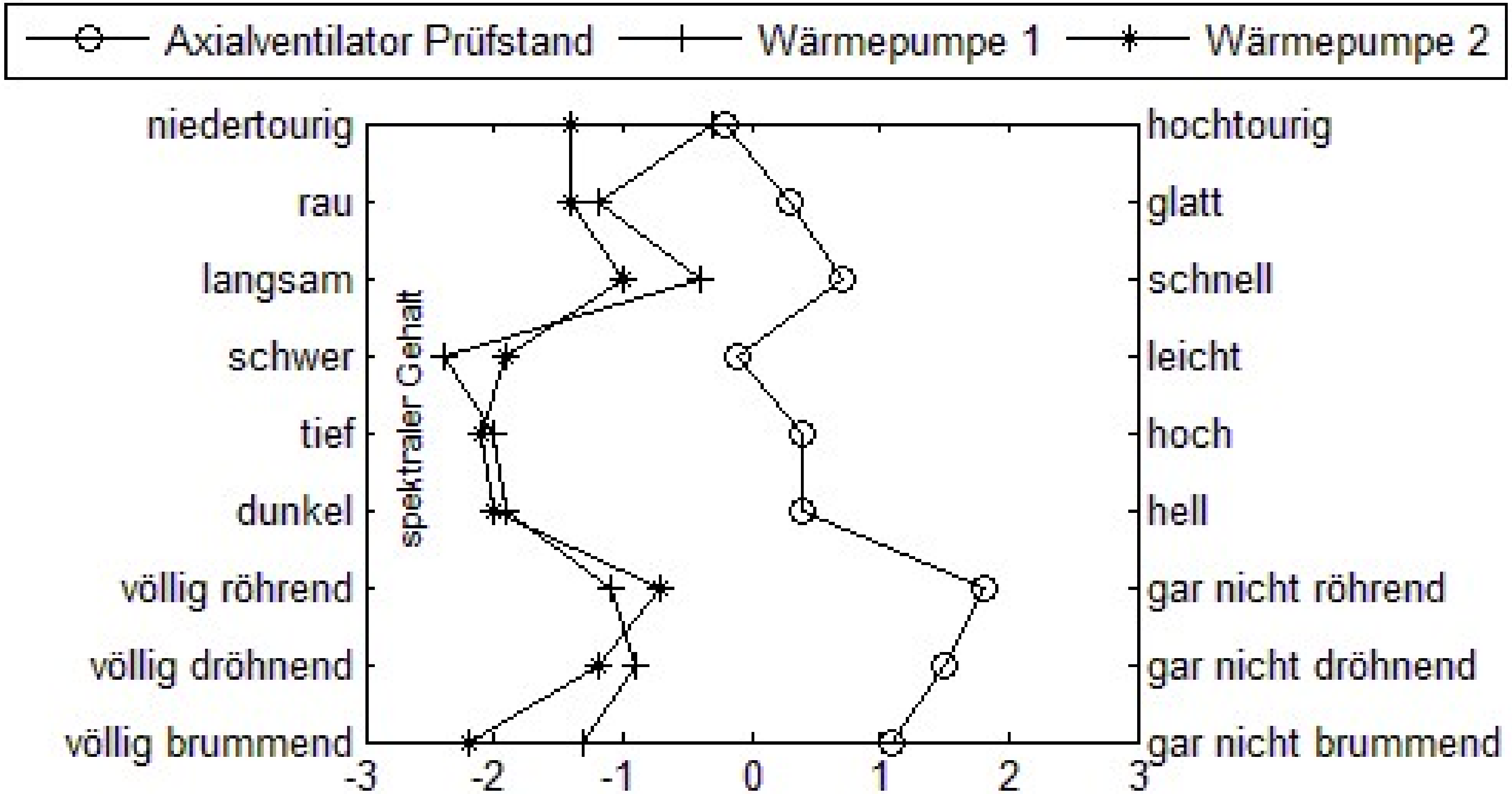
## How to predict sound quality

- Eventually, the sound quality of a given sound is a linear combination of these psychoacoustic metrics:

$$\text{Quality} = \sum_j k_j (j \text{ objective psychoacoustic metrics})$$

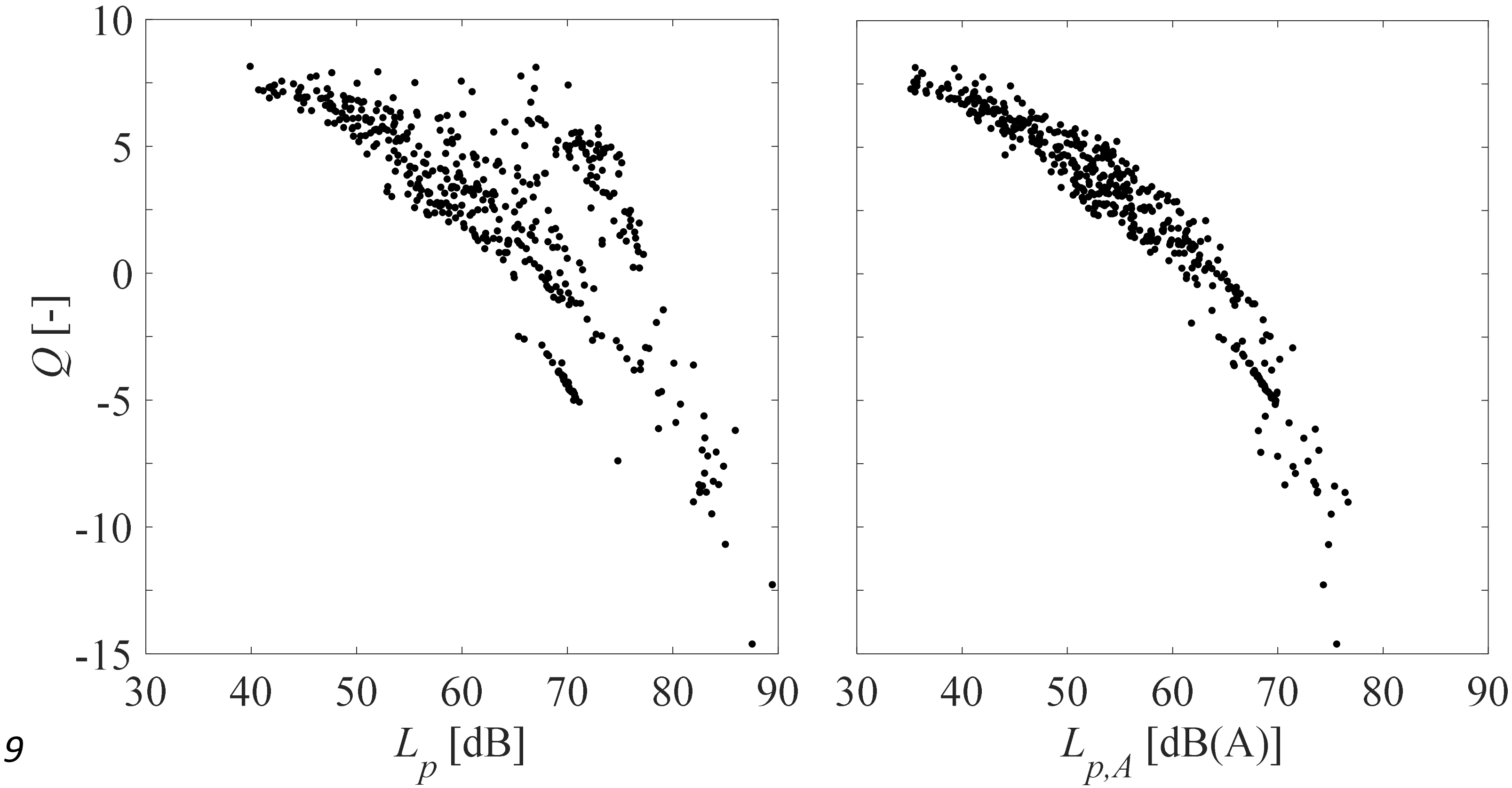
Their individual weights $k_j$ are the results of the jury listening test.

# Example: Jury assessment of three different fan sounds

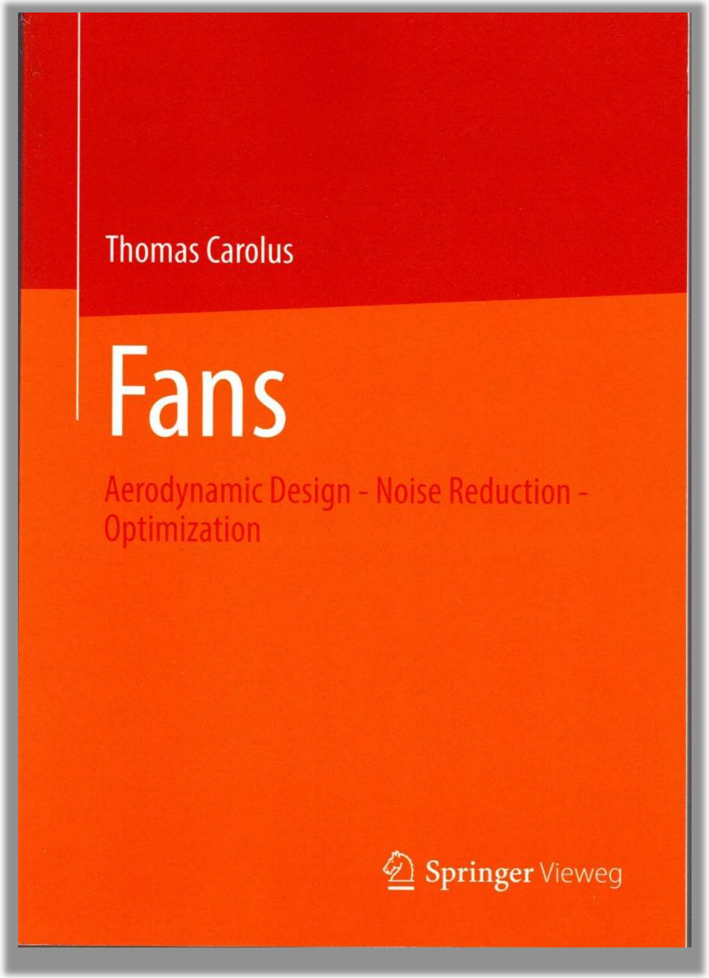


## Example

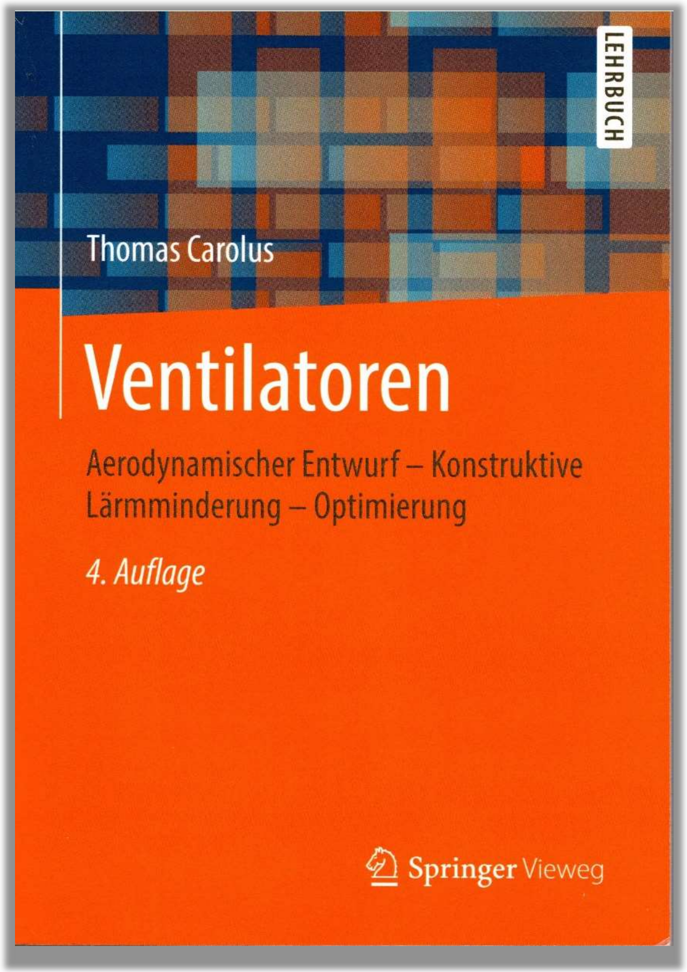
486 fans and devices with fans: Predicted sound quality *Q* from measured spectra




*Feldmann, University Siegen 2019*



Thomas Carolus
Fans
Aerodynamic Design - Noise Reduction - Optimization
Springer Vieweg

LEHRBUCH
Thomas Carolus
Ventilatoren
Aerodynamischer Entwurf – Konstruktive Lärmminderung – Optimierung
4. Auflage
Springer Vieweg

# Part 4:

# Open issues

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?

- Does simulation replace experiments, now, in the future, ....?
- What expertise is required to run meaningful and reliable numerical flow simulations?
- Integration of flow noise into the design process.
- High-fidelity aurealisation, a dream?
- Simulation of the complete system/device, not just the isolated fan performance.

- Thinking of innovative manufacturing methods for more exotic shapes (without neglecting structural health).

- How to keep the fundamental technical knowledge about the fluid mechanics of turbomachinery alive?
- ............................

# Vielen Dank!

For further information contact

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