Aerodynamic Noise Reduction with Flow Control Devices


SA Public Workshop, 26 November 2020
Outline

• Introduction
• Leading-Edge Noise Treatments
• Trailing-Edge Noise Treatments
• Boundary-Layer Separation control
• Industrial Perspective and Applications
• Q&A
I. INTRODUCTION
Aerodynamic Noise is Everywhere

ENERGY PRODUCTION

TRANSPORTATION

PERSONAL APPLIANCES
Can We Blame Turbulence?

High Reynolds number ➔ turbulence

Turbulence-Interaction Noise

Sound radiation from a turbofan fan stage [1]

Blade-vortex interaction on helicopter [2]

Airfoil Self-Noise

Turbulent boundary layer

Forced flow matching

Noise radiation from trailing edge

Wind turbine sound source map [1]

Aircraft-on-approach source map [2]


Wind Turbine Noise and Complaints

Wind Turbine Noise and Complaints

De Telegraaf
Eerste NL’se klimaatvluchtelingen een feit: ’Windangst, het lawaai is niet te harden’

Door EDWIN TIMMER
31 okt. 2020 in BINNENLAND


Why Noise Mitigation is Important?

Evolution of wind turbine heights and output

1-12kW 0.5 MW 1.2 MW 2 MW 4 MW 7 MW 9 MW 13-15 MW

Sources: Various; Bloomberg New Energy Finance
Why Noise Mitigation is Important?

Power curtailment is no longer needed
Or
Higher energy production within the noise limit
Aircraft Noise

Development of aircraft noise emissions

Lateral noise level standardized to 500 KN EPNdB

-88% (-30 dB)

Year of registration

Number of seats
200  400  600  800

B707-120
B727-100
A300-B4-605R
B737-300
A340-600
A380-842
B787-8
A319neo Leap

Aircraft Noise

Boeing 707[1]
Turbojet

1960s

Boeing 777[2]
High-bypass turbofan

2000s

[1] Kuwait airways 707, Pinterest
[3] https://www.nap.edu/read/23490/chapter/6#36
Aircraft Noise

[1] Kuwait airways 707, Pinterest
[3] https://www.nap.edu/read/23490/chapter/6#36
[4] Lecture 6 Turbojet Turbofan Increasing thrust, CHALMER
Potential Solutions

HOW CAN WE ACHIEVE NOISE REDUCTION?

1. Sound absorption
2. Noise source intensity attenuation
3. Acoustic interference

PROMISING FLOW CONTROL DEVICES?

Porous materials  Serrations  Vortex Generators
TIN Reduction by Wavy Leading Edge Serrations

TIN Reduction
by Wavy Leading Edge Serrations

Flat-plate  NACA 0012

‘Tuned’ serrations,

\[ L \leq 4\Lambda \]

P. Chaitanya et al. JFM, 2017
Basic Noise Reduction Mechanisms

• Destructive interference of the scattered surface pressure [1]

• Cutoff effect due to the oblique edge [2]


Experimental Results
Baseline versus Serrated Flat-Plates

- Higher noise reductions occur at ~5 kHz over all radiation angles
Experimental Results
Baseline versus Serrated Flat-Plates

- Higher noise reductions occur at ~5 kHz over all radiation angles
Airfoil TEN contribution to the Total Airfoil Noise

Beamforming

Far-field microphone

Bampanis *et al.*, AIAA 2019
Comparison of Predictions with Experiments

- Good agreement at low and mid frequencies
- Possible future improvement by applying a shear-layer refraction correction.
- Discrepancies at high frequencies due to the trailing-edge noise contribution. (TEN is not included in the analytical modelling).
The porous airfoil includes a rigid skeleton with a center plate with recessed edge, filled with porous material. A smooth surface is ensured by covering the assembly with a wiremesh.
Far-Field Estimates of TIN Reduction on Porous Airfoils

Full-chord center plate (V1)

Recessed-edge center plate (V2)

Flow speed: 32 m/s
0° AOA
Rotor-Stator Interaction Noise

Rotor-stator interaction in turbofan

Typical turbofan noise power spectra

Noise spectra of rod – airfoil configuration @ 75m/s [1]

Noise and LE Treatment Types

5406-SLE  5406-PLE  5406-SPLE  5406-WLE

Ni-Cr-Al metal foam block

Noise and LE Treatment Types

Comparison of source power level (PWL)

PWL reduction for different LE treatments

Aerodynamic Analysis

<table>
<thead>
<tr>
<th></th>
<th>$\Delta C_{l\text{,mean}}$ (%)</th>
<th>$\Delta C_{d\text{,mean}}$ (%)</th>
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<tr>
<td>5406-WLE</td>
<td>-5.36</td>
<td>5.73</td>
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<td>5406-PLE</td>
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<tr>
<td>5406-PWLE</td>
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<td>35.35</td>
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</table>

Comparison of mean surface pressure distribution


Aerodynamic Analysis

VKI rod-airfoil configuration

Solid airfoil

Porous airfoil

NACA-0024 airfoil

cylindrical rod (d = 0.02 m)

side-plates

Acoustic muffle

Exhausting fan

Flow direction

Acoustic isolation and anechoic treatment

Contraction

Turb. reduct. grids

Flow direction

$U_\infty$  $Re_d$

30 m/s  40,800

$\overline{x/d}$

7.85

0.157 m

0.174 m

0.040 m

s = 0.2 m

[1] Zamponi et al., 25th AIAA/CAES, 2019

[1] Zamponi et al., 25th AIAA/CAES, 2019
**VKI porous airfoil**

**NACA-0024 profile**

<table>
<thead>
<tr>
<th>Material</th>
<th>$\phi$ [%]</th>
<th>$\sigma$ [Pa s m$^{-2}$]</th>
<th>$\alpha_\infty$ [-]</th>
<th>$\Lambda$ [m]</th>
<th>$\Lambda'$ [m]</th>
<th>$k'$ [m$^2$]</th>
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<td>Melamine foam</td>
<td>98.6</td>
<td>8,683</td>
<td>1.02</td>
<td>$1.344 \times 10^{-4}$</td>
<td>$1.942 \times 10^{-4}$</td>
<td>$2.305 \times 10^{-9}$</td>
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<tr>
<td>Exo-skeleton</td>
<td>80.0</td>
<td>~ 0</td>
<td>~</td>
<td>~</td>
<td>~</td>
<td>~</td>
</tr>
<tr>
<td>Wire-mesh</td>
<td>60.8</td>
<td>~ 0</td>
<td>~</td>
<td>~</td>
<td>~</td>
<td>~</td>
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</table>

**Determination of melamine foam parameters according to the JCAL model**\[^{1-3}\]

Airfoil layers characterization

4 samples of melamine foam are characterized by means of an impedance tube to analyze the sound absorbing behavior of the porous material[1]

\[ \alpha = 1 - R^2 \]

<table>
<thead>
<tr>
<th>Emitted signal</th>
<th>Emission frequency range</th>
<th>Acquisition frequency range</th>
</tr>
</thead>
<tbody>
<tr>
<td>White noise</td>
<td>50 - 5.000 Hz</td>
<td>80 - 4.300 Hz</td>
</tr>
</tbody>
</table>

[1] Satcunanathan et al., INTER-NOISE, 2019
Acoustic beamforming proved to be an effective tool to properly isolate noise source contributions and evaluate airfoil-turbulence interaction noise\textsuperscript{[1]}

\textbf{Absolute sound pressure levels}

\textbf{Relative sound pressure levels}

What is the origin of the noise reduction?

\textsuperscript{[1]} Zamponi et al., Journal of Sound and Vibration, 2020
How Does Porosity Affect the Flow?

Vortices distortion at LE

Air flow circulation within the airfoil

Boundary-layer characteristics

Airfoil potential effect
The flow field in the stagnation region is studied through LES\cite{1}

Turbulence intensity

\begin{equation}
\frac{u'}{U_\infty} \quad \frac{v'}{U_\infty}
\end{equation}

Turbulent Kinetic Energy (TKE)

\begin{equation}
\begin{align*}
\text{Solid airfoil} & \quad \text{Porous airfoil} \\
\end{align*}
\end{equation}

\cite{1} Zamponi et al., Journal of Sound and Vibration, 2020
The turbulence distortion is attenuated for a porous airfoil\cite{1}

*Turbulence distortion mechanisms*\cite{2}

- Blocking of velocity fluctuations by the pressure of the body
- Distortion of vorticity field by the mean flow

\cite{1} Zamponi et al., *Journal of Sound and Vibration*, 2020
\cite{2} Zamponi et al., *Journal of Fluid Mechanics*, Under review
Wall-Pressure Fluctuations

Solid airfoil

Porous airfoil

Solid
Porous

\[ \text{PSD}_{p'p'} \left[ \text{dB/Str} \right] \]

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\[ \text{St} = \frac{fd}{V_\infty} \]

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Trailing-edge serrations

- Trailing edge serrations are widely used noise reduction devices;
- Still there is a lack of information on the effects of the flow on the noise reduction:
  - High spatial and temporal resolution information required;
- Well designed trailing edge serrations can improve noise reduction in respect to the standard sawtooth.

Goal

Novel flow diagnostics for trailing-edge serration assessment

- Unsteady flow (pressure) over trailing-edge serrations;
- High spatial and temporal resolution required for aeroacoustic study.

Time-resolved 3D-PIV
- Lower temporal resolution;
- Higher spatial resolution;
- Velocity field only (reconstruct pressure);
- Restricted interrogation volume;
- Post processing chain.

Unsteady surface pressure sensors
- High temporal resolution;
- Limited spatial resolution;
- Pressure field;
- Model installation.
**3D-PIV - Post Processing**

- **Particles**
- **Pressure**

- 3D-PIV using Helium Filled Soap Bubbles:
  - Flow measurements in a large domain;
- Shake the box particle tracking (3D-LPT):
  - Particle location and velocity;
- VIC+:
  - Gridded velocity field;
- Pressure reconstruction:
  - \[ \nabla^2 P = -\rho \nabla \cdot \frac{D\vec{V}}{Dt}. \]
• Secondary flow formed on the serrations undergoing aerodynamic loading (vortex pairs along the serration);
• Alterations of the pressure fluctuations along the serration;
• Implications on far-field noise.
Far field noise measurements

- Sawtooth serrations:
  - Better noise reduction without loading;
  - High sensitivity to the loading condition;
- Combed sawtooth:
  - Similar noise reduction levels without loading;
  - Less sensitive to increasing of aerodynamic loading.
Porous Trailing Edge

- Porous trailing-edge (TE) has shown promising noise-reduction capability [1,2].
- Flow communication across the porous medium is essential for noise mitigation [2].
- Porous TE has lower scattering efficiency compared to the porous one [2].
- Which part of the porous TE is more important for promoting noise reduction?

NACA 0018 with porous TE insert

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Diamond Trailing Edge

NACA 0018 + Diamond (DMND) TE

0.2c = 4 cm

DMND TE

Impermeable partition

DB49 TE

Unit-cell

Ø1.2 mm
6.36 mm

Graphs showing variations in $\Phi_n$ and $\Delta\Phi_n$ with Stc.
Correlation Statistics

Entrance length

\[ D = \text{unit-cell size} \]
\[ d_p = \text{mean pore size} \]

Local TE thickness normalised by unit-cell/pore dimension

Streamwise correlation length of surface pressure fluctuations

\[ L_{ee} \]

\[ x/c \]
Correlation Statistics

A relatively thin and long porous TE extent might be desirable.

Entrance length

\[ D \text{ = unit-cell size} \]
\[ d_p \text{ = mean pore size} \]

Local TE thickness normalised by unit-cell/pore dimension

Noise reduction spectra

Streamwise correlation length of surface pressure fluctuations
1st Q/A SESSION
IV. SEPARATION CONTROL
• Design conditions: flow and acoustic analysis of wind turbine profiles/blades available.

Off design condition – boundary layer flow separation

• Adverse pressure gradients at high inflow angles and wind speeds.
• Causes aerodynamic losses, stall and lower performance.
• To tackle detached flow, various flow control devices have been used.

Flow control devices

• Delay and reduce separation thus improving aerodynamic performance.
• First proposed by Taylor (1948)[1] for aircrafts.
• Existing devices: Streamwise vortex generators (vane, delta, air jet etc.)

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Off design condition: Novel flow control device – Rod Vortex Generators (RVGs)\(^1\) for boundary layer separation.

RVGs investigated for **Helicopter** rotor blades\(^2\), **Wind turbine profiles/rotors**\(^3\).

*Acoustic impact on wind turbine applications?*

1. **Loading** noise due to pressure variations (dominant at low Mach).
2. **Thickness** noise due to rotation.
3. **Quadrupole** noise (neglected).

Limitations of helicopter operating in forward flight\(^2\)

**Off design condition**: Novel flow control device – Rod Vortex Generators (RVGs)\(^1\) for boundary layer separation.

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*Acoustic impact on wind turbine applications?*

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2. **Thickness** noise due to rotation.
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Contour plot of Mach number and streamlines at cross section of advancing helicopter rotor blade in forward flight.
RESEARCH INTRODUCTION

Off design condition: Novel flow control device – Rod Vortex Generators (RVGs)\(^1\) for boundary layer separation.

RVGs investigated for Helicopter rotor blades\(^2\), Wind turbine profiles/rotors\(^3\).

Acoustic impact on wind turbine applications?

1. Loading noise due to pressure variations (dominant at low Mach).
2. Thickness noise due to rotation.
3. Quadrupole noise (neglected).

Contour maps of skin friction coefficient and flow streamlines for NREL Phase VI wind turbine rotor\(^3\)

\(^1\) P. Doerffer, 2009.
Design of RVGs for measurements of a wind turbine profile **DU96-W-180** with/without RVGs at **TU Delft**.

**Test section**: Anechoic vertical open-jet wind tunnel (rectangular section - 40 x 70 cm², contraction ratio of 15:1).

**Numerical design of RVGs**: 
- Full wind tunnel approach – including sideplates, jet nozzle.
- Profile: Chord = 0.15m, span = 0.4m, Reynolds number = 2.63 x 10⁵.
- Mesh: Hybrid mesh (Numeca Hexpress), RANS 3D simulations (Fine Open, EARSM model).

\[ V = 30 \text{ m/s, } \text{AoA} = 10^0 \]

\[ V = 30 \text{ m/s, } \text{AoA} = 13^0 \]

\[ V = 30 \text{ m/s, } \text{AoA} = 15^0 \]

*Separation zone and corner vortices grow along with increasing inflow angles*
DEIGN OF RVGS FOR DU96-W-180 PROFILE

• Design of RVGs for measurements of a wind turbine profile DU96-W-180 with/without RVGs at TU Delft.
• Test section: Anechoic vertical open-jet wind tunnel (rectangular section - 40 x 70 cm², contraction ratio of 15:1).
• RVGs design parameters:
  - Height = 2mm and 3mm.
  - Diameter = 0.8 mm.
  - Number of rods = 47.
  - Distance between the rods = 8 mm.
EXPERIMENTAL CAMPAIGN (1)

Oil flow visualization for non-tripped DU96-W-180 profile at AoA = 17°

Acoustic beamforming for DU96-W-180 profile at AoA = 6°

Sound pressure analysis
At low frequency: \( \text{SPL}_{\text{RVG}} < \text{SPL}_{\text{Clean}} \)
At mid frequency: \( \text{SPL}_{\text{RVG}} \approx \text{SPL}_{\text{Clean}} \)
At high frequency: \( \text{SPL}_{\text{RVG}} > \text{SPL}_{\text{Clean}} \)
Oil flow visualization for tripped DU96-W-180 profile at AoA = 6°

Acoustic beamforming for DU96-W-180 profile at AoA = 6°

Sound pressure analysis
At low frequency: \( \text{SPL}_{\text{RVG}} < \text{SPL}_{\text{Clean}} \)
At mid frequency: \( \text{SPL}_{\text{RVG}} \sim \text{SPL}_{\text{Clean}} \)
At high frequency: \( \text{SPL}_{\text{RVG}} > \text{SPL}_{\text{Clean}} \)
Acoustic beamforming for DU96-W-180 profile at AoA = 6°

Source maps for DU96-W-180 profile for AoA = 6° at low frequency

*An noisier source map for the clean case at trailing edge*
Experimental Campaign (2)

Acoustic beamforming for DU96-W-180 profile at AoA = 6°

Reference

RVGs

Source maps for DU96-W-180 profile for AoA = 6° at mid frequency

A noisier source map for the RVGs case with source spreading at trailing edge
A noise source due to the jet is visible at the nozzle exit
EXPERIMENTAL CAMPAIGN (2)

Acoustic beamforming for DU96-W-180 profile at AoA = 6°

Reference

Source maps for DU96-W-180 profile for AoA = 6° at high frequency

A noisier source map for the RVGs case with source spreading at trailing edge
A noise source due to the jet is visible at the nozzle exit
Noise sources due to corner vortices at the side plates are also visible
AERO-ACOUSTIC CODE

Theory: Ffowcs Williams – Hawkings analogy (Farassat’s formulations)

\[ p'(\vec{x}, t) = \frac{\partial}{\partial t} \int_S \frac{\rho_0 v_n}{r|1 - M_r|} dS - \frac{\partial}{\partial x_i} \int_S \frac{P_{ij} n_j}{r|1 - M_r|} dS + \frac{\partial^2}{\partial x_i \partial x_j} \int_V \frac{T_{ij}}{r|1 - M_r|} dV \]

- Monopole (thickness term)
- Dipole (loading term)
- Quadrupole (volume term)

Acoustic code:

1. Development.
2. Validation
   - Stationary:
     1. Monopole
     2. Dipole
3. Applications

Analytical

Experiment + Other codes

Observer time

Acoustic pressure
AERO-ACOUSTIC CODE

Theory: Ffowcs Williams – Hawkings analogy (Farassat’s formulations)

\[ p'(\bar{x}, t) = \frac{\partial}{\partial t} \iint_S \frac{\rho_0 v_n}{r|1 - M_r|} \, dS - \frac{\partial}{\partial x_i} \iiint_S \frac{p_{ij} n_j}{r|1 - M_r|} \, dS + \frac{\partial^2}{\partial x_i \partial x_j} \iint_V \frac{T_{ij}}{r|1 - M_r|} \, dV \]

Monopole (thickness term)

Dipole (loading term)

Quadrupole (volume term)

Acoustic code:

1. Development.
2. Validation
3. Applications
   • Rotating:
     3. Monopole
     4. Dipole
     5. Source-sink pair

Analytical

Experiment + Other codes

Observer time

Thickness term

Acoustic pressure

Total acoustic pressure (Pa)

Observer time (s)

Analytical

FW-H code
AEREO-ACOUSTIC CODE

Theory: Ffowcs Williams – Hawkings analogy (Farassat’s formulations)

\[
p'(\bar{x},t) = \frac{\partial}{\partial t} \oint_s \frac{\rho_0 v_n}{r|1-M_r|} \, dS - \frac{\partial}{\partial x_i} \oint_s \frac{p_{ij} n_j}{r|1-M_r|} \, dS + \frac{\partial^2}{\partial x_i \partial x_j} \oint_V \frac{T_{ij}}{r|1-M_r|} \, dV
\]

\begin{align*}
\text{Monopole} & & (\text{thickness term}) \\
\text{Dipole} & & (\text{loading term}) \\
\text{Quadrupole} & & (\text{volume term})
\end{align*}

Acoustic code:

1. Development
   - Rotating:
     3. Monopole
     4. Dipole
     5. Source-sink pair

2. Validation

3. Applications
   - Analytical
   - Experiment + Other codes

---

### Loading term

- **Analytical**
- **FW-H code**

---

### Total acoustic pressure (Pa)

- 80
- 70
- 60
- 50
- 40
- 30
- 20
- 10
- 0
- -10

---

### Observer time (s)

- 0.01
- 0.02
- 0.03
- 0.04

---

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AERO-ACOUSTIC CODE

Theory: Ffowcs Williams – Hawkings analogy (Farassat’s formulations)

\[ p'(\vec{x},t) = \frac{\partial}{\partial t} \int_S \left[ \frac{\rho_0 v_n}{r|1 - M_r|} \right] dS - \frac{\partial}{\partial x_i} \int_S \left[ \frac{p_{ij} n_j}{r|1 - M_r|} \right] dS + \frac{\partial^2}{\partial x_i \partial x_j} \int_V \left[ \frac{T_{ij}}{r|1 - M_r|} \right] dV \]

- Monopole (thickness term)
- Dipole (loading term)
- Quadrupole (volume term)

Acoustic code:

1. Development.
2. Validation
3. Applications

- Helicopter rotor

Analytical

Experiment + Other codes

Acoustic pressure vs time graph

Experiment
Literature
FW-H code
AERO-ACOUSTIC CODE

Theory: Ffowcs Williams – Hawkings analogy (Farassat’s formulations)

\[ p'(\bar{x},t) = \frac{\partial}{\partial t} \iint_S \frac{\rho_0 v_n}{r |1 - M_r|} dS - \frac{\partial}{\partial x_i} \iint_S \left( \frac{p_{ij} n_j}{r |1 - M_r|} \right) dS + \frac{\partial^2}{\partial x_i \partial x_j} \iiint_V \left( \frac{T_{ij}}{r |1 - M_r|} \right) dV \]

- **Monopole** (thickness term)
- **Dipole** (loading term)
- **Quadrupole** (volume term)

**Acoustic code:**

1. **Development.**
2. **Validation**
3. **Applications** • Wind turbine blade with RVGs
• **Experiment**: NREL’s Unsteady Aerodynamics Experiment on horizontal axis wind turbines\(^1\)
  - Phase VI: 24 m x 36m wind tunnel
  - Rotor with 2 blades, 10 m diameter, rotational speed = 72 rpm

• **Pressure data** from steady flow simulations (MAREWINT project\(^2\)) as input to the developed aero-acoustic code.

Flow simulations\(^2\) were validated against measurements\(^1\)

\[ V = 7 \text{ m/s} \quad r/R = 0.80 \]

Pressure coefficient of NREL blade at flow velocity $V = 7 \text{ m/s}^{[3]}$

Acoustic pressure for clean NREL Phase VI blade

\[ J \text{ Suarez et al. Wind Energy, 2018} \]

\[ [1] \text{ M.M. Hand, et al. Unsteady Aerodynamics Experiment Phase VI: Wind Tunnel Test Configurations and Available Data Campaigns.} \]

\[ [2] \text{ J Suarez et al. Wind Energy, 2018} \]
Leading-edge serrations

Ziehl-Abegg, 2016

Zenger, Renz, and Becker, 2017

Zenger, Renz, and Becker, 2017

Krömer, Czwielong, & Becker, 2019
Trailing-edge serrations

Oerlemans et al. 2009

Pagliaroli et al. 2018

Lee, Lim, & Lee, 2018

Siemens-Gamesa 2000

Ziehl-Abegg 2012
Vortex generators

Gloster Javelin FAW9 (BAE Systems), 1956

3M & EDF, 2014

Symphony SA-160, 2001

Lufthansa, 2014
Experiments on a plenum fan

- Diameter 361 mm
- Blade span 98 mm
- 7 blades
- $N_{\text{maxi}} = 1470$ rpm

<table>
<thead>
<tr>
<th>Nom</th>
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<th>$h$ [mm]</th>
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</table>
Leading edge, N=1440 rpm

Pressure curves

Specific sound levels at outlet

\[ L_{p,\text{specific}} = L_p - 10 \log(q_v) - 20\log(p_f) \]
Leading edge, BEP, N=1440 rpm

Specific noise spectra

Specific noise reduction
Trailing edge, N=1440 rpm

Pressure curves

Specific noise levels at outlet

\[ L_{p,\text{specific}} = L_p - 10 \log(q_v) - 20\log(p_f) \]
Trailing edge, BEP, N=1440 rpm

Specific noise spectra

Specific noise reduction
Specific noise levels at outlet

Specific noise spectra

Laminar boundary-layer vortex-shedding $f \cdot \frac{\nu}{V} \approx 1$
VI. CONCLUDING REMARKS
What’s next?

• Further investigation of the underlying physics of noise reduction by the use of serrations, porous materials, and vortex generators.

• To predict the impact of these novel noise mitigation techniques and their applications on an industrial scale.
WHY DID WE UNDERTAKE THIS ADVENTURE?

“If we knew what it was we were doing, it would not be called research, would it?”

-Albert Einstein

"You cannot hope to build a better world without improving the individuals. To that end each of us must work for his own improvement, and at the same time share a general responsibility for all humanity, our particular duty being to aid those to whom we think we can be most useful."

-MARIE CURIE

Physicist & Chemist
Thank you for your attention!