PhD Defense

Experimental study of broadband trailing edge noise of a linear cascade and its reduction with passive devices

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Introduction

Noise reduction

Why aircraft noise is to be reduced?

Orly airport noise disturbance map.
- Red: LDEN > 70, Blue: LDEN > 65, Orange: LDEN > 55. [ACNUSA]

Noise problems nearby airports.
Introduction

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Noise problems nearby airports.

Fan noise contribution

Engine of an A380 aircraft

Take-off and landing: \( \leq 40\% \).
Introduction

Discriminating fan noise sources

Fan noise composition

- **Tonal noise**, significantly reduced in the past decades,
- **Broadband noise**, still to be reduced.

Many broadband noise sources near the rotor

**Figure:** Axial flow compressor rotor flow phenomena [AGARD-AG-328].
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- Turbulence - Shock Surface interaction noise,

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- Stall noise ...

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**Figure**: Axial flow compressor rotor flow phenomena [AGARD-AG-328].
Blades are not isolated in a fan!

- Reflections,
- Resonances,
- Duct propagation ...
Introduction

Cascade Effect

Blades are not isolated in a fan!

- Reflections,
- Resonances,
- Duct propagation ...

Literature: few studies on cascade trailing edge noise

- Analytical modeling: Howe 92; Glegg 98;
- Experiments: Parker 66, Sabah & Roger 01.
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Cascade Effect

Blades are not isolated in a fan!

- Reflections,
- Resonances,
- Duct propagation ...

Literature: few studies on *cascade* trailing edge noise

- Analytical modeling: Howe 92; Glegg 98;
- Experiments: Parker 66, Sabah & Roger 01.

Need for cascade noise experiment & model validation.
Introduction

Objectives

This study aims at

- Designing an aeroacoustic cascade set-up,
- Measuring cascade TBL-TE noise with various \( U_1, \alpha_1 \)...
- Assessing the extent of the cascade effect,
- Validating existing cascade noise models,
- Reducing cascade noise.
Outline

1. Cascade Experiment
   - Set-up
   - Aerodynamic Loading
   - Cascade Acoustics

2. Analytical Model Validation
   - Input Data for Models
   - Amiet’s Isolated Airfoil Noise Model
   - Glegg’s Cascade Noise Model

3. Cascade Noise Reduction
   - Set-up
   - Acoustic Results
   - PIV results
   - Noise reduction mechanisms
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Experiment
Set-up of a unique linear cascade

Linear cascade of 7 NACA 6512-10 airfoils, studied by Emery\(^1\).

<table>
<thead>
<tr>
<th>Chord</th>
<th>(c)</th>
<th>100 mm</th>
<th>(\sigma = c/s)</th>
<th>1.43</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pitch</td>
<td>(s)</td>
<td>70 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upstream velocity</td>
<td>(U_1)</td>
<td>80 m/s</td>
<td>(M)</td>
<td>0.23</td>
</tr>
<tr>
<td>Span</td>
<td>(L)</td>
<td>200 mm</td>
<td>(Re)</td>
<td>(5.3 \times 10^5)</td>
</tr>
</tbody>
</table>

\(^1\) Systematic two-dimensional cascade tests of NACA 65-series compressor blades at low speeds, NACA report 1368, 1957
Experiment

Improvements from Sabah’s set-up

2001 : Sabah’s PhD thesis

- Aim : measurement of cascade leading edge and trailing edge noise,
- High background noise level.
Experiment
Improvements from Sabah’s set-up

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- Aim : measurement of cascade leading edge and trailing edge noise,
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Some improvements
- Side panels,
- Brushes at the end of wood boards,
- No boundary layer exhaust.
Experiment
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Downstream far-field acoustic spectra

- Sabah ;
- Kevlar walls ;
- Kevlar walls without BL exhaust ;
- Metal walls without BL exhaust
⇒ downstream measurements only.
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Aerodynamic Loading
Validating the cascade design point

Reference point near maximum efficiency

\[ \alpha_1 = 15^\circ, \beta_1 = 35^\circ, U_1 = 80 \text{ m/s}. \]  

\( (\sigma = 1.43) \)
Aerodynamic Loading

Validating the cascade design point

Reference point near maximum efficiency

\[ \alpha_1 = 15^\circ, \; \beta_1 = 35^\circ, \; U_1 = 80 \text{ m/s.} \quad (\sigma = 1.43) \]

Control on center blade.

- Measurement,
- Bock RANS computation,
- Emery & al.,
  \( (\alpha_1 = 14.1^\circ, \; \beta_1 = 30^\circ, \; \sigma = 1.5) \)
- Sabah.
Aerodynamic Loading

Validating the cascade design point

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\[ \alpha_1 = 15^\circ, \beta_1 = 35^\circ, U_1 = 80 \text{ m/s}. \quad (\sigma = 1.43) \]

Control on center blade.

- Measurement
- Bock RANS computation
- Emery & al., \((\alpha_1 = 14.1^\circ, \beta_1 = 30^\circ, \sigma = 1.5)\)
- Sabah

Control on other blades.

At 50% chord,
- Suction Side
- Pressure Side
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Velocity Dependence
Specific frequency scaling

Far-field PSD at \( r=2 \text{ m} \)
Scaling to \( U_1 = 80 \text{ m/s} \) using PSD \( \propto U_1^6 \),
Frequency axis unchanged \( \Rightarrow \) \( \text{He}=\frac{fL}{c_0} \) rather than \( \text{St}=\frac{f\delta^*}{U_1} \).
Acoustic Resonances
Near-field / far-field coherence

Remote Surface Unsteady Pressure Probes

Near the center blade trailing edge, midspan plane

- To measure entry data of analytical models (boundary layer statistics),
- To investigate near-field/far-field coherence.
Acoustic Resonances
Near-field / far-field coherence

Remote Surface Unsteady Pressure Probes

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Parker Resonances:

\[ \theta < 0^\circ, \quad \theta > 0^\circ. \]
Acoustic Resonances
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Parker
Resonances :

\[ \theta < 0^\circ, \quad \theta > 0^\circ. \]

\[ \beta, \alpha, \gamma \]

\[ \gamma^2 \text{ vs. } \text{frequency, } \text{Hz} \]
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Parker
Resonances:

\[ \theta < 0^\circ, \quad \theta > 0^\circ. \]
Acoustic Interference
Visible in far-field measurements

Blade-to-blade reflections

![Graph showing PSD vs frequency](image)
Acoustic Interference
Visible in far-field measurements

Blade-to-blade reflections

![Graph showing acoustic interference](image-url)
Acoustic Interference
Visible in far-field measurements

Blade-to-blade reflections

\[ |1 - e^{ik(\delta_1 + \delta_2)}| \]
Acoustic Interference
Visible in far-field measurements

Blade-to-blade reflections

\[ |1 - e^{ik(\delta_1 + \delta_2)}| \]
Acoustic Interference
Visible in far-field measurements

Blade-to-blade reflections

Most obvious cascade effects have been observed
To go further, need for analytical modeling: computation of the cascade transfer function.
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Input Data Measurement: BL Statistics

$q \rightarrow \Phi_{pp}(\omega)$

![Graph showing PSD in dB vs. frequency in Hz for Cascade and Isolated airfoil, with annotations indicating similar performance.

On center blade,

\[ U_1 \approx 70 \text{ m/s}, \]
\[ \alpha_1 = 35^\circ, \]
\[ \beta = 45^\circ. \]
Input Data Measurement: BL Statistics

\[ \Phi_{pp}(\omega) \]

\[ l_z = \int_0^{+\infty} \gamma(\omega, \eta) \cos(Kz\eta) d\eta \]

On center blade,
\[ U_1 \simeq 70 \text{ m/s}, \]
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Input Data Measurement: BL Statistics

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\[ U_c \]

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Analytical Models

Amiet’s isolated airfoil TE noise model

Isolated airfoil formulation:

\[
S_{pp}^{(n)}(x, y, z, \omega) = 2L \left( \frac{\omega y c}{4\pi c_0 S_0^2} \right)^2 \left| \mathcal{I} \left( \frac{\omega}{U_c}, 0 \right) \right|^2 \Phi_{pp}(\omega) l_z \left( \frac{k z}{S_0} = 0, \omega \right)
\]

7 independent airfoils, observer in the midspan plane, infinite span, shear layer refraction.

[Graph depicting airfoils and measurement vs prediction]
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Glegg’s Analytical Model

Original formulation

Linear cascade model
- Fan azimuthal periodicity ⇒ periodic sources in linear cascade
- Small numbers of propagating modes,
- BL information in $Q$,
- 3D: $K = (K_x, K_z)$.

\[
p_s = \frac{-2\pi i}{Bh} \sum_{m=-\infty}^{m=+\infty} Q H_m(K_x) e^{-i\omega t + iK_z z} \frac{K_m e^{-i\gamma_m (x - yd/h) - 2i\pi my/Bh}}{(2\pi)^2 i(\gamma_m + K_x) J_+^{(m)}(-K_x) J_-^{(m)}(\gamma_m)}
\]
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$\bar{\omega} = 1 \Rightarrow 1$ propagative mode.
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\]

$\Re(p_s)$, Pa

$\bar{\omega} = 1 \Rightarrow 1$ propagative mode.

$\bar{\omega} = 3 \Rightarrow 5$ propagative modes.
Glegg’s Analytical Model
Choice of Periodicity Parameter $B$

Choosing $B$ with the aim of isolating a single source contribution.

![Graph showing $\Re(p_s)$ values with color gradient from blue to red, indicating positive values. The x-axis is labeled $x, m$ ranging from -1 to 3, and the y-axis is labeled $y, m$ ranging from -1 to 1. The image depicts a 2D distribution with a color scale ranging from -0.06 to 0.06 Pa. The notation $B=30$ is indicated at the bottom right corner.]
Glegg’s Analytical Model
Choice of Periodicity Parameter $B$

Choosing $B$ with the aim of isolating a single source contribution.

Graphs showing the real part of pressure ($\mathcal{R}(p_s)$) with $B=30$ and $B=100$.
Glegg’s Analytical Model
Choice of Periodicity Parameter $B$

Choosing $B$ with the aim of isolating a single source contribution.
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Choice of Periodicity Parameter $B$

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Glegg’s Analytical Model
Choice of Periodicity Parameter $B$

Choosing $B$ with the aim of isolating a single source contribution.

![Diagram showing the effect of different $B$ values on the model output](#)
Glegg’s Analytical Model
Comparison with acoustic measurements

Last Steps:
- Expressing $Q$ in terms of $\Phi_{pp}, l_z, U_c$,
- Integrating on $K_z$,
- Summing over independent blade contributions.
Glegg’s Analytical Model
Comparison with acoustic measurements

Last Steps:
- Expressing $Q$ in terms of $\Phi_{pp}, l_z, U_c$,
- Integrating on $K_z$,
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Results:
Slight modulation of single airfoil results (3 dB).

![Graph showing comparison between measurement, Glegg’s model, and Amiet’s model.](image)
Three noise models have been adapted to the test case:

- Amiet’s isolated airfoil TE noise model,
- Glegg’s cascade TE noise model,
- Howe’s cascade TE noise model (not shown).
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Results show that:

- Cascade effect $\simeq 3$ dB,
- Experiment variation close to model discrepancies,
- Cascade CPU (10min) $\gg$ Isolated Airfoil CPU (1 sec).
Analytical Models

Conclusions

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Cascade TE noise measured and may be reduced.
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Cascade TBL-TE Noise Reduction

Successful *isolated* airfoil noise reduction

- Many passive devices tested in the FLOCON EU project,
- TE serrations gave best results & were down-selected.
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⇒ Does the noise reduction also occur in a *cascade*?
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Cascade TBL-TE Noise Reduction

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- TE serrations gave best results & were down-selected.

⇒ Does the noise reduction also occur in a *cascade*?

Serrations sketches

- Straight edge
- Short serrations
  \[ \lambda_c = 2 \text{ mm}, \ 2h = 13 \text{ mm} \]
- Long serrations
  \[ \lambda_c = 2 \text{ mm}, \ 2h = 20 \text{ mm}, \]
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Serration Acoustic Results
Far field noise reduction, suction side direction $\theta = 40^\circ$

- Very similar results to single airfoil noise reduction,
- Single airfoil $St_0=1.18$; Cascade $St_0=1.21$. 
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Near Wake Dynamics
Mean Velocity $\overline{U_x}$

Observations
- Serration wake larger and less deep,
- Serrations : through flow with a $10^\circ$ angle.
Near Wake Dynamics
Fluctuating velocity $u'_x$

**Observations**

- BL removed from the airfoil surface,
- Smaller turbulent area in the pressure side wake.
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Serrations
Investigation of noise reduction mechanisms

Serrations may reduce noise through:
- BL ejection,
- Spanwise decorrelation,
- Local sweep angle? → Analytical investigations.
Serrations
Investigation of noise reduction mechanisms

Serrations may reduce noise through:

- BL ejection,
- Spanwise decorrelation,
- Local sweep angle? → Analytical investigations.

Modified Amiet model for sweep angle $\varphi$:

*Step 1: Airfoil response function - compressible unsteady aerodynamics*
Serrations
Investigation of noise reduction mechanisms

Modified Amiet model for sweep angle $\varphi$:

*Step 2: Far-field scattering - Curle’s theory*

\[ L \omega = \begin{cases} 1, \\ 5, \\ 10, \\ 20. \end{cases} \]

Conclusions:
- Serration details cannot be analytically reproduced $\Rightarrow$ only a hint,
- This new model could be useful for fan noise prediction,
- Decrease of noise power in $\cos \varphi^3$. 
Conclusions

Cascade Experiment

- Cascade rig significantly improved,
- Cascade trailing edge noise measured,
- Specific cascade effects observed and analysed.

Analytical models

- Input data measured in cascade,
- Amiet’s model give reasonable prediction ±3 dB above 200 Hz,
- Glegg’s cascade model adapted to the experiment,
- It differs from Amiet’s model in level by ±3 dB,
  ⇒ need for increasing cascade effect via $\sigma$. 
Cascade noise reduction

- Serration inserted in cascade,
- Reduction at low frequencies,
- No influence of cascade effect on noise reduction,
- Candidate mechanism to noise reduction:
  - BL removal,
  - Spanwise decorrelation,
  - Local sweep angle,
- Amiet’s model modified for sweep angle.
Thank you for your attention!