*PhD Defense*

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


Arthur Finez

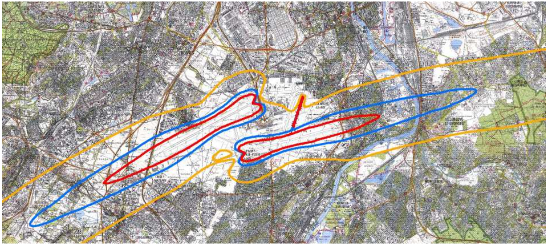
LMFA/École Centrale de Lyon


Thursday 10th May 2012

# Introduction

## Noise reduction

### Why aircraft noise is to be reduced ?



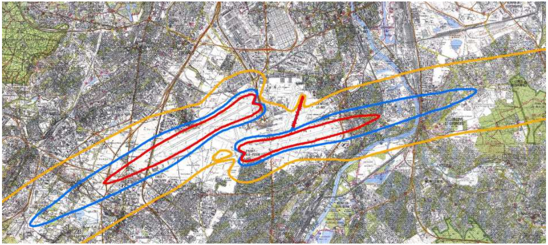
Orly airport noise disturbance map.
— : LDEN>70, — : LDEN>65, — : LDEN>55. [ACNUSA]

Noise problems nearby airports.

# Introduction

## Noise reduction

### Why aircraft noise is to be reduced ?



Orly airport noise disturbance map.
— : LDEN>70, — : LDEN>65, — : LDEN>55. [ACNUSA]

Noise problems nearby airports.

### Fan noise contribution

Engine of an A380 aircraft

Take-off and landing : $\simeq 40\%$.

# 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

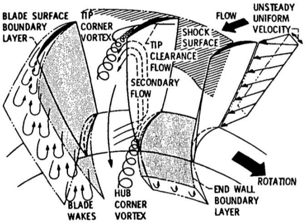



FIGURE: Axial flow compressor rotor flow phenomena [AGARD-AG-328].

# 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

- Turbulence - Leading Edge (LE) interaction noise,

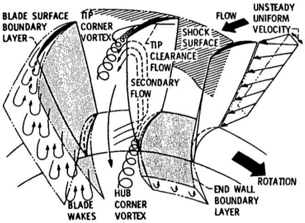



FIGURE: Axial flow compressor rotor flow phenomena [AGARD-AG-328].

# 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

- Turbulence - Leading Edge (LE) interaction noise,
- Turbulent Boundary Layer (TBL) - Trailing Edge (TE) interaction noise,

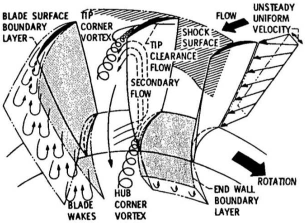



FIGURE: Axial flow compressor rotor flow phenomena [AGARD-AG-328].

# 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

- Turbulence - Leading Edge (LE) interaction noise,
- Turbulent Boundary Layer (TBL) - Trailing Edge (TE) interaction noise,
- Blade Tip noise,

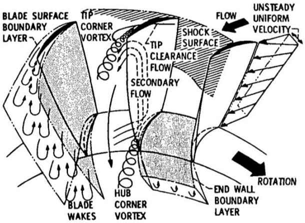



FIGURE: Axial flow compressor rotor flow phenomena [AGARD-AG-328].

# 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

- Turbulence - Leading Edge (LE) interaction noise,
- Turbulent Boundary Layer (TBL) - Trailing Edge (TE) interaction noise,
- Blade Tip noise,
- Turbulence - Shock Surface interaction noise,

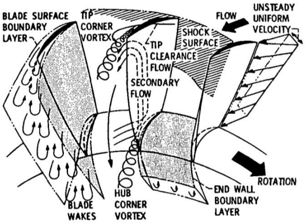



FIGURE: Axial flow compressor rotor flow phenomena [AGARD-AG-328].

# 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

- Turbulence - Leading Edge (LE) interaction noise,
- Turbulent Boundary Layer (TBL) - Trailing Edge (TE) interaction noise,
- Blade Tip noise,
- Turbulence - Shock Surface interaction noise,
- Stall noise ...

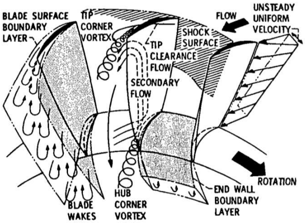



FIGURE: Axial flow compressor rotor flow phenomena [AGARD-AG-328].

# Introduction

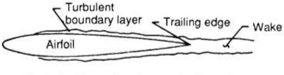
## Discriminating fan noise sources

### Fan noise composition

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

### Many broadband noise sources near the rotor

- Turbulence - Leading Edge (LE) interaction noise,
- Turbulent Boundary Layer (TBL) - Trailing Edge (TE) interaction noise,




- Blade Tip noise,
- Turbulence - Shock Surface interaction noise,
- Stall noise ...

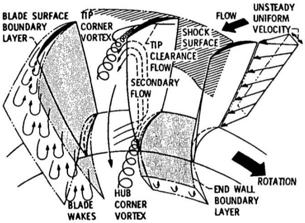


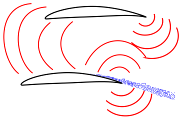

FIGURE: Axial flow compressor rotor flow phenomena [AGARD-AG-328].

# Introduction

## Cascade Effect

### Blades are not isolated in a fan !

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

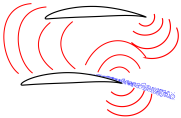


# Introduction

## Cascade Effect

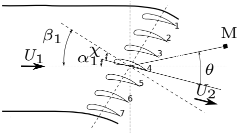
### Blades are not isolated in a fan !

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



### Literature : few studies on *cascade* trailing edge noise

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

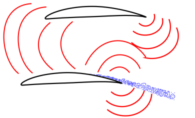


# Introduction

## Cascade Effect

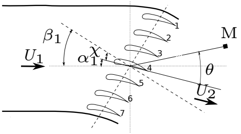
### Blades are not isolated in a fan !

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



### Literature : few studies on *cascade* trailing edge noise

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




### 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.

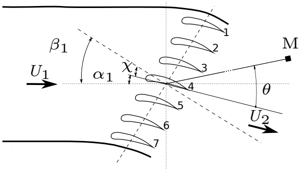
# Outline

# Outline

# Experiment

## Set-up of a unique linear cascade

Linear cascade of 7 NACA 6512-10 airfoils, studied by Emery [1].




| | | | | | |
|---|---|---|---|---|---|
| Chord | $c$ | 100 | mm | $\sigma = c/s$ | 1.43 |
| **Pitch** | $s$ | 70 | mm | | |
| Upstream velocity | $U_1$ | 80 | m/s | M | 0.23 |
| Span | $L$ | 200 | mm | Re | $5.3 \times 10^5$ |

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

### 2001 : Sabah's PhD thesis

- Aim : measurement of cascade leading edge and trailing edge noise,
- High background noise level.

### Some improvements

- Side panels,
- Brushes at the end of wood boards,
- No boundary layer exhaust.

# Experiment

## Improvements from Sabah's set-up

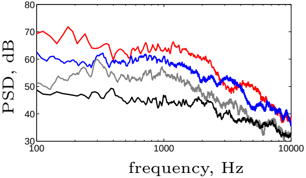
### 2001 : Sabah's PhD thesis

- Aim : measurement of cascade leading edge and trailing edge noise,
- High background noise level.

### Some improvements

- Side panels,
- Brushes at the end of wood boards,
- No boundary layer exhaust.

### Downstream far-field acoustic spectra




- Sabah ;
- Kevlar walls ;
- Kevlar walls without BL exhaust ;
- Metal walls without BL exhaust

⇒ downstream measurements only.

# Outline

# Aerodynamic Loading

## Validating the cascade design point

**Reference point near maximum efficiency**

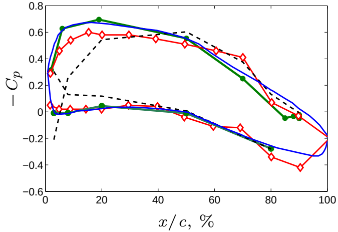
$\alpha_1 = 15°$, $\beta_1 = 35°$, $U_1 = 80$ m/s. $(\sigma = 1.43)$

# Aerodynamic Loading

## Validating the cascade design point

### Reference point near maximum efficiency

$\alpha_1 = 15°,\ \beta_1 = 35°,\ U_1 = 80$ m/s. $(\sigma = 1.43)$




### Control on center blade.

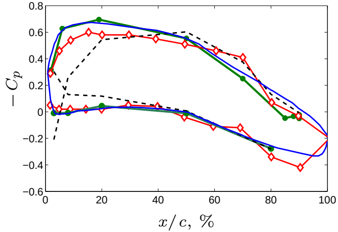
- Measurement,
- Bock RANS computation,
- Emery & al., ($\alpha_1 = 14.1°$, $\beta_1 = 30°$, $\sigma = 1.5$)
- Sabah.

# Aerodynamic Loading

## Validating the cascade design point

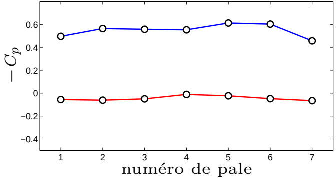
### Reference point near maximum efficiency

$\alpha_1 = 15°,\ \beta_1 = 35°,\ U_1 = 80$ m/s. $(\sigma = 1.43)$




### Control on center blade.

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




### Control on other blades.

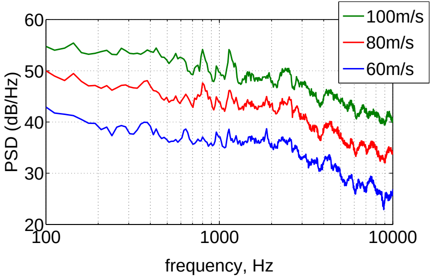
At 50% chord,
- Suction Side,
- Pressure Side.

# Outline

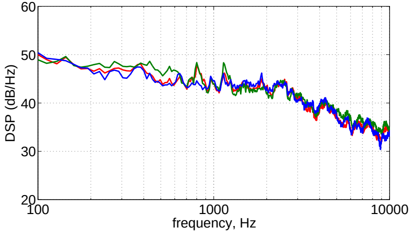
# Velocity Dependence

## Specific frequency scaling

**Raw PSD**




**Scaled PSD**




### Far-field PSD at r=2 m

Scaling to $U_1$ =80 m/s using PSD $\propto U_1^6$,

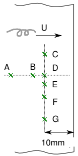
Frequency axis unchanged $\Rightarrow$ He$=\frac{fL}{c_0}$ rather than St$=\frac{f\delta^*}{U_1}$.

# Acoustic Resonances

## Near-field / far-field coherence

### Remote Surface Unsteady Pressure Probes

Near the center blade trailing edge, midspan plane

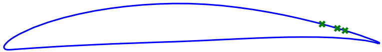



- To measure entry data of analytical models (boundary layer statistics),
- To investigate near-field/far-field coherence.

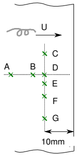
# Acoustic Resonances

## Near-field / far-field coherence

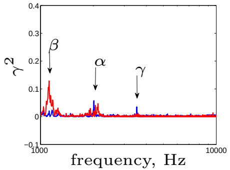
### Remote Surface Unsteady Pressure Probes



Near the center blade trailing edge, midspan plane

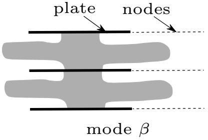



- To measure entry data of analytical models (boundary layer statistics),
- To investigate near-field/far-field coherence.




— $\theta < 0°$,
— $\theta > 0°$.

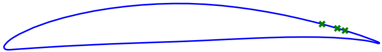
Parker Resonances :



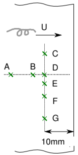
# Acoustic Resonances

## Near-field / far-field coherence

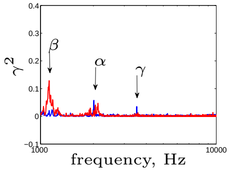
### Remote Surface Unsteady Pressure Probes



Near the center blade trailing edge, midspan plane

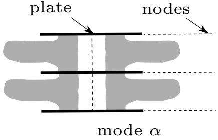



- To measure entry data of analytical models (boundary layer statistics),
- To investigate near-field/far-field coherence.




— $\theta < 0°$,
— $\theta > 0°$.

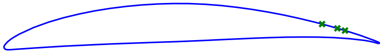
Parker Resonances :



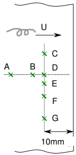
# Acoustic Resonances

## Near-field / far-field coherence

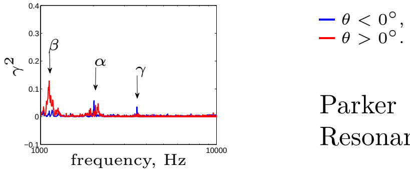
### Remote Surface Unsteady Pressure Probes



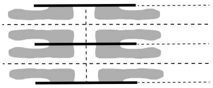
Near the center blade trailing edge, midspan plane




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




Parker Resonances :

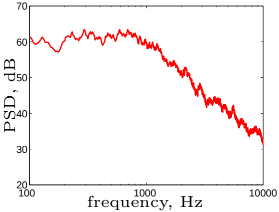


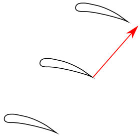
mode $\gamma$

# Acoustic Interference

## Visible in far-field measurements

### Blade-to-blade reflections

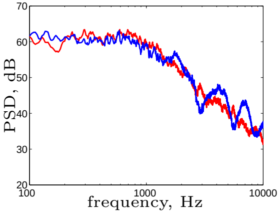


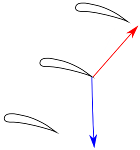



# Acoustic Interference

## Visible in far-field measurements

### Blade-to-blade reflections

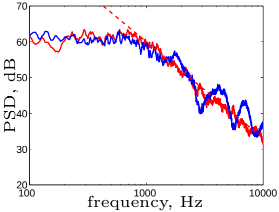


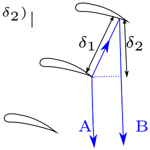
# Acoustic Interference

## Visible in far-field measurements

### Blade-to-blade reflections



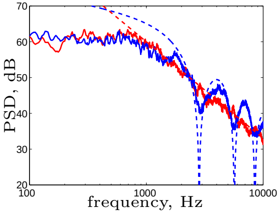

$$|1 - e^{ik(\delta_1 + \delta_2)}|$$



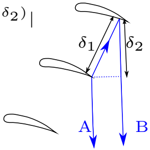
# Acoustic Interference

## Visible in far-field measurements

### Blade-to-blade reflections



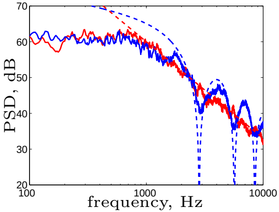

$$|1 - e^{ik(\delta_1+\delta_2)}|$$



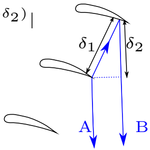
# Acoustic Interference

## Visible in far-field measurements

### Blade-to-blade reflections




$$|1 - e^{ik(\delta_1 + \delta_2)}|$$



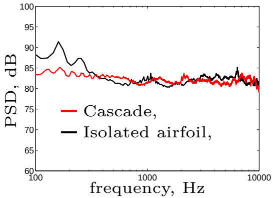

### Most obvious cascade effects have been observed

To go further, need for analytical modeling : computation of the cascade transfer function.

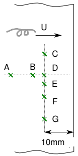
# Outline

# Input Data Measurement : BL Statistics

↬ $\Phi_{pp}(\omega)$

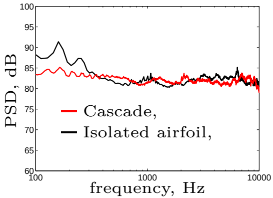



On center blade,
$U_1 \simeq 70$ m/s,
$\alpha_1 = 35^\circ$,
$\beta = 45^\circ$.

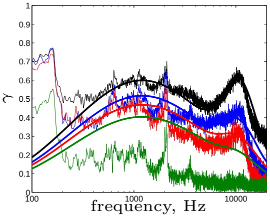


# Input Data Measurement : BL Statistics

↬ $\Phi_{pp}(\omega)$

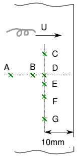



↬ $l_z = \int_0^{+\infty} \gamma(\omega,\eta)\cos(K_z\eta)\mathrm{d}\eta$



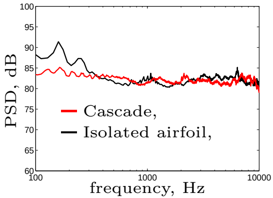

$\eta$ (mm) : — 1, — 2.5, — 3.5, — 5.

On center blade,
$U_1 \simeq 70$ m/s,
$\alpha_1 = 35^\circ$,
$\beta = 45^\circ$.

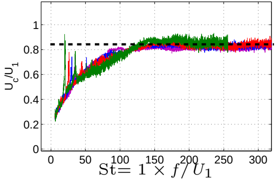


# Input Data Measurement : BL Statistics

↬ $\Phi_{pp}(\omega)$

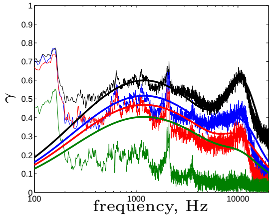



↬ $U_c$



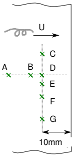

$U_1$, m/s
60,
70,
80,
100.

↬ $l_z = \int_0^{+\infty} \gamma(\omega,\eta)\cos(K_z\eta)\mathrm{d}\eta$




$\eta$ (mm) : — 1, — 2.5, — 3.5, — 5.

On center blade,
$U_1 \simeq 70$ m/s,
$\alpha_1 = 35^\circ$,
$\beta = 45^\circ$.



# Outline

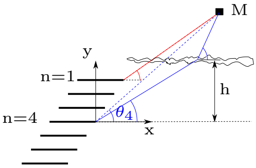
# Analytical Models

## Amiet's isolated airfoil TE noise model

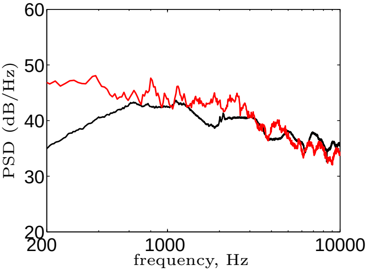
### Isolated airfoil formulation :

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

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




— Measurement,
— Prediction,



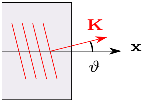
# Outline

# 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 : $\mathbf{K} = (K_x, K_z)$.



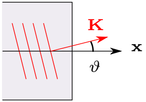

$$p_s = \frac{-2\pi i}{Bh} \sum_{m=-\infty}^{m=+\infty} Q H_m(K_x) e^{-i\omega t + iK_z z} \frac{K_m^- e^{-i\gamma_m^-(x-yd/h)-2i\pi my/Bh}}{(2\pi)^2 i(\gamma_m^- + K_x) J_+^{(m)}(-K_x) J_-^{(m)}(\gamma_m^-)}$$

# Glegg's Analytical Model

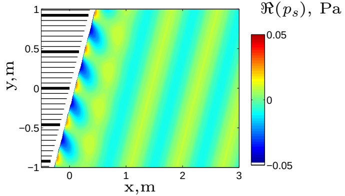
## Original formulation

### Linear cascade model

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




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



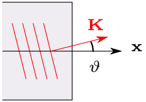

$\overline{\omega} = 1 \Rightarrow 1$ propagative mode.

# Glegg's Analytical Model

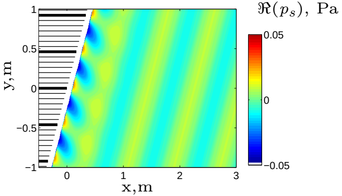
## Original formulation

### Linear cascade model

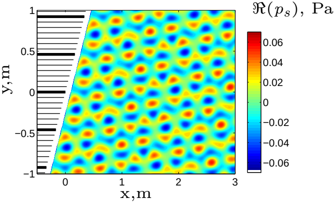
- Fan azimuthal periodicity ⇒ periodic sources in linear cascade
- Small numbers of propagating modes,
- BL information in $Q$,
- 3D : $\mathbf{K} = (K_x, K_z)$.




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




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

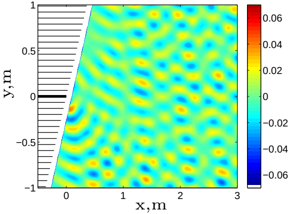



$\overline{\omega} = 3 \Rightarrow 5$ propagative modes.

# Glegg's Analytical Model

## Choice of Periodicity Parameter $B$

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




$\Re(p_s)$, Pa

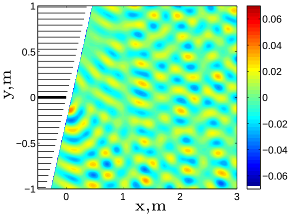
**B=30**

# Glegg's Analytical Model

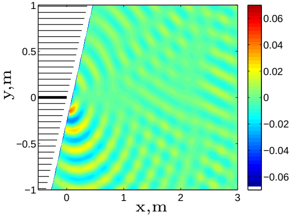
## Choice of Periodicity Parameter $B$

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

$\Re(p_s)$, Pa




**B=30**

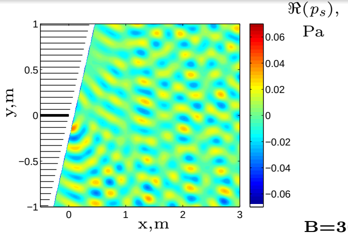



**B=100**

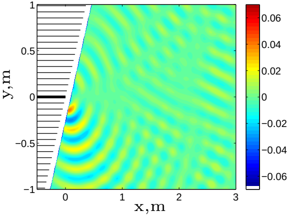
# Glegg's Analytical Model

## Choice of Periodicity Parameter $B$

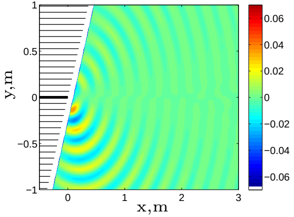
Choosing $B$ with the aim of isolating a single source contribution.




**B=30**




**B=100**

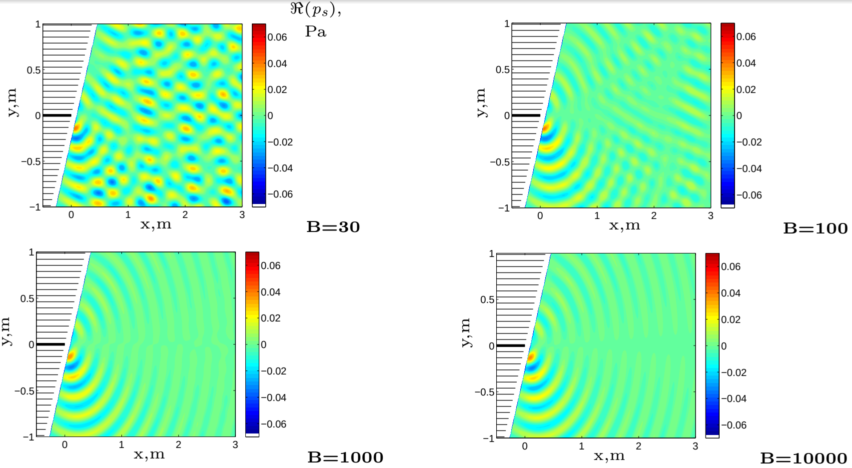



**B=1000**

# Glegg's Analytical Model

## Choice of Periodicity Parameter $B$

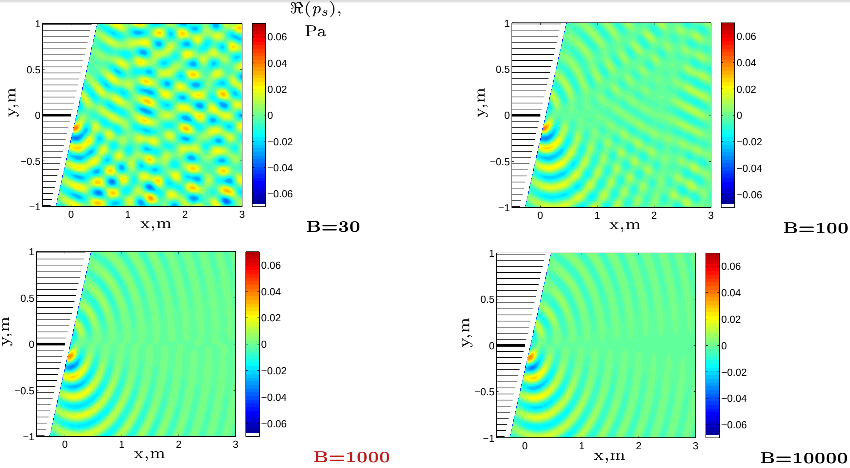
Choosing $B$ with the aim of isolating a single source contribution.



# Glegg's Analytical Model

## Choice of Periodicity Parameter $B$

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



# 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 independant blade contributions.

# Glegg's Analytical Model

## Comparison with acoustic measurements

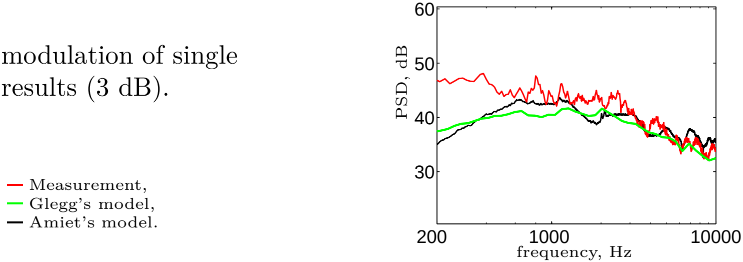
Last Steps :

- Expressing $Q$ in terms of $\Phi_{pp}, l_z, U_c$,
- Integrating on $K_z$,
- Summing over independant blade contributions.

Results :

Suction side $\theta = 40°$

Slight modulation of single airfoil results (3 dB).



# Analytical Models

## Conclusions

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).

# Analytical Models

## Conclusions

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).

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

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).

Results show that :

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

Cascade TE noise measured and may be reduced.

# Outline

# Introduction

## 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.

# Introduction

## 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.

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

# Introduction

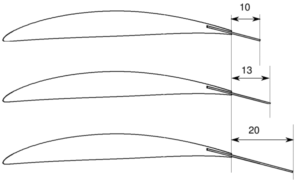
## Cascade TBL-TE Noise Reduction

### Successful *isolated* airfoil noise reduction

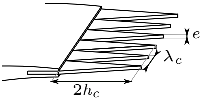
- Many passive devices tested in the FLOCON EU project,
- TE serrations gave best results & were down-selected.

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

### Serrations sketches



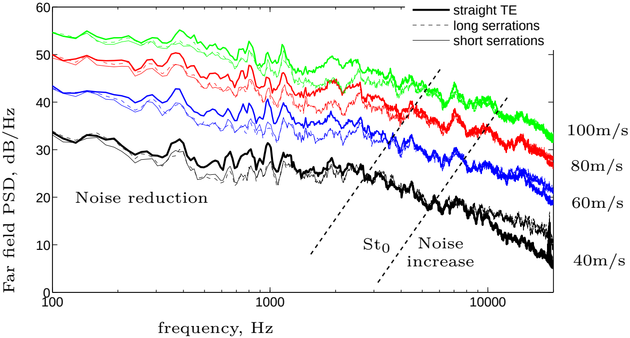

- Straight edge
- Short serrations
  $\lambda_c = 2$ mm, $2h = 13$ mm
- Long serrations
  $\lambda_c = 2$ mm, $2h = 20$ mm,



# Outline

# Serration Acoustic Results

## Far field noise reduction, suction side direction $\theta = 40^\circ$



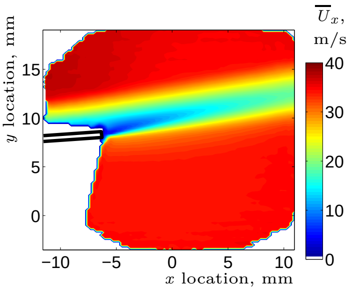

- Very similar results to single airfoil noise reduction,
- Single airfoil $St_0$=1.18 ; Cascade $St_0$=1.21.

# Outline

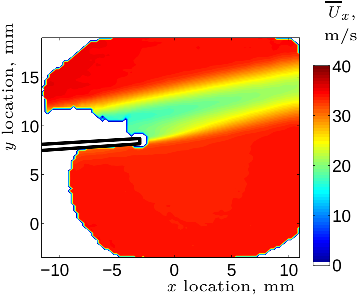
# Near Wake Dynamics

## Mean Velocity $\overline{U}_x$

### Straight Edge

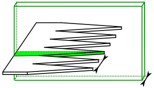



### Serrated Edge




### Observations

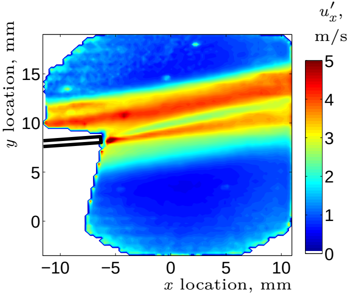
- Serration wake larger and less deep,
- Serrations : through flow with a 10° angle.



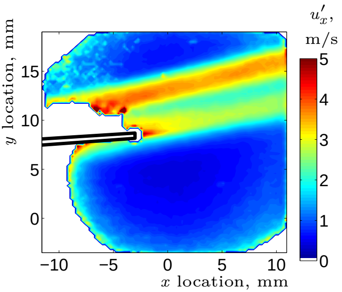
# Near Wake Dynamics

## Fluctuating velocity $u'_x$

Straight Edge

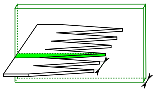



Serrated Edge




### Observations

- BL removed from the airfoil surface,
- Smaller turbulent area in the pressure side wake.



# Outline

# Serrations

## Investigation of noise reduction mechanisms

Serrations may reduce noise through :

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

# Serrations

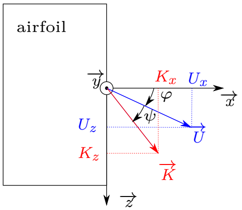
## Investigation of noise reduction mechanisms

Serrations may reduce noise through :

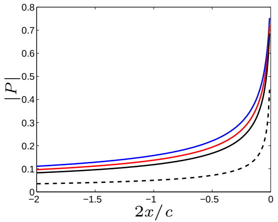
- BL ejection,
- Spanwise decorrelation,
- Local sweep angle ? → Analytical investigations.

Modified Amiet model for sweep angle $\varphi$ :

*Step 1 : Airfoil response function - compressible unsteady aerodynamics*




— $\varphi = 0°$,
— $\varphi = 15°$,
— $\varphi = 60°$,
- - $\varphi = 85°$.

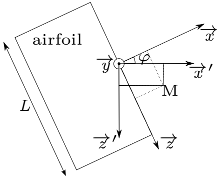


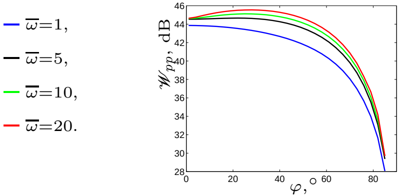
# Serrations

## Investigation of noise reduction mechanisms

### Modified Amiet model for sweep angle $\varphi$ :

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




### 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 $\pm 3$ dB above 200 Hz,
- Glegg's cascade model adapted to the experiment,
- It differs from Amiet's model in level by $\pm 3$ dB,
  $\Rightarrow$ need for increasing cascade effect via $\sigma$.

# Conclusions

## 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 !