# AEROACOUSTICS

## Numerical analysis of the impact of porous media on trailing-edge noise

13 November 2018 | Seong-Ryong Koh | SimLab Fluids & Solids Engineering, JSC

# OUTLINE

1. Introduction
   - Sound generation in fluid mechanics
   - Computational aeroacoustics (CAA)
2. Motivation
3. Objectives
4. Numerical method
   - Volume-averaging approach: parameters of porous media
   - Flow configuration
     - Porous structure
     - LES/CAA domain
5. Results
   - Acoustic fields determined by a variable porosity
   - Acoustic fields at a finite angle-of-attack
6. Summary



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# WAVE IN FLUID MECHANICS

## Aerodynamic sound

- Wave and Vibration in a dynamic system
  - Involve a balance between a restoring force and intertia of a system
  - External restoring force, e.g., gravity, surface tension, tube elasticity, magnetic force, Coriolis force

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- Wave motions with external restoring force are anisopropic!
  - Dispersion relation, e.g., wave speed as a function of wavenumber
  - Exception, e.g., water surface waves in 2D horizontal propagation.

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- Sound generated aerodynamically
  - Restoring force balancing the fluid's intertia provided by its own **compressibility** (mass conservation)
  - Compressibility properties are same in all directions, i.e., isotropic sound propagation
  - Compressibility implies, the density of a fluid changes!

# WAVE IN FLUID MECHANICS

## Classical acoustic theories

have considered

1. linear wave propagation,
2. single frequency (or harmonics),
3. constant flow properties (no spatial gradient),
4. and simple geometry (or just in free space).

- Acoustic waves in aerodynamics were understood via linear acoustic theories. So called, ‘aeroacoustics’ indicates the noise generation by aerodynamic phenomena.
- <u>Linear</u> wave propagation in subsonic flows


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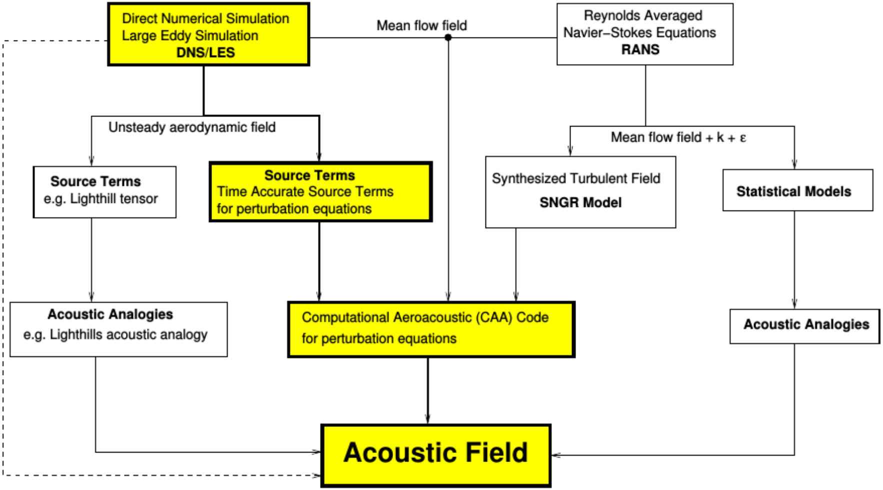
# COMPUTATIONAL AEROACOUSTICS (CAA)

## What is CAA?

- Employment of Computational Fluid Dynamics (CFD) techniques in the direct calculation of all physical properties in sound generation and wave propagation
- Numerical solution of fundamental differential or integral equations of the fluid motion
  - Acoustic sources
  - Wave propagation
  - Speed of sound

# COMPUTATIONAL AEROACOUSTICS (CAA)

## CAA classification



# COMPUTATIONAL AEROACOUSTICS (CAA)

## Challenges to CAA

- Small size of quantities of interest:
  $p'_{\text{acoustics}} \ll p'_{\text{hydrodynamic}}$
- High-frequencies of quantities of interest:
  $f_{\text{max}}$ based on the spatial resolution
- Long time solutions necessary:
  to analyze low-frequency components (large $\lambda_{\text{min}}$)
- Damping and dispersion of oscillations undesirable:
  low-pass filter to remove unresolved high-frequencies
- Non-reflecting boundary conditions required

# COMPUTATIONAL AEROACOUSTICS (CAA)

## Numerical schemes for CAA

CAA requires equal attentions be paid to both *time and space derivatives* which are not usually considered in CFD.

- Usually requires accurate statistics in the frequency domain
- Extremely large storage required to resolve wave propagation

# COMPUTATIONAL AEROACOUSTICS (CAA)

## Numerical schemes for CAA

CAA requires equal attentions be paid to both *time and space derivatives* which are not usually considered in CFD.

- Usually requires accurate statistics in the frequency domain
  1. High-order time integration method
  2. Numerical dispersion/dissipation
  3. Long-time computation for high-resolution analysis

- Extremely large storage required to resolve wave propagation
  1. High-order spatial discretization scheme
  2. Numerical dispersion/dissipation
  3. Huge computational domain for high-resolution analysis



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# COMPUTATIONAL AEROACOUSTICS (CAA)

## Resource usage for an LES/CAA simulation

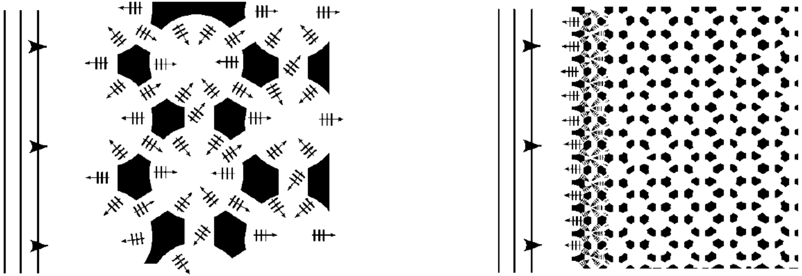
| | year 2008 | year 2016 |
|---|---|---|
| jet model | isolated jet | real scale nozzle |
| jet Mach number | $\mathrm{Ma} = 0.9$ | $\mathrm{Ma} = 0.1$ |
| | | |
| # of cells (LES) | $20 \times 10^6$ | $330 \times 10^6$ |
| # of cells (CAA) | $12 \times 10^6$ | $100 \times 10^6$ |
| resolved freq. range | $\mathrm{St} < 2$ | $\mathrm{St} < 10$ |
| | | |
| MPI processors | 64 cores | 6000 cores |
| LES runtime | 1 week | <1 week |
| post proc. & CAA runtime | 1-2 weeks | 1 week |
| disk usage | $\mathcal{O}(10^2)$ Gb | $\mathcal{O}(10)$ Tb |

Koh et al., *J. Sound Vib.*, 329, 2010. Cetin et al., *Flow Turbul. Combust.*, 98(2), 2017. Cetin et al., *Comput. Rendus Mecanique*, 346, 2018

# NOISE REDUCTION VIA POROUS MEDIA

## Porous medium and noise attenuation

Acoustic wave is assumed isentropic and frictionless in gas. However, in reality the viscous effect changes the acoustic energy being dissipated into heat. e.g., inside porous media.



*Schematic of acoustic energy dissipation via porous media as changing the pore-size.*

Ref.: Kuczmarski, M., Johnston, J. C., NASA/TM-2011-216995, 2011.

# MOTIVATION

- **Noise reduction via porous media**
  - Acoustic energy dissipation
  - Turbulent flows and the associated acoustic sources modified by porous media
- **Parameters influencing acoustic attenuation performance**
  - Structure size ($\mathbf{d_p}$)
  - Flow resistance ($\mathbf{R_s}$)
  - Porosity ($\psi$)
  - Tortuosity (fluid networks), thickness, installation, etc.
- Relationship between the porous parameters and the turbulent flows, e.g., non-dimensional variables in inner scales.
  - Roughness Reynolds number ($\mathbf{Re_d}$)
  - Permeability Reynolds number ($\mathbf{Re_K}$)

# MOTIVATION

- **Noise reduction via porous media**
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- **Parameters influencing acoustic attenuation performance**
  - Structure size (**$d_p$**)
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- Relationship be… …ws, e.g., non-dimen…
  - Roughness…
  - Permeabilit…

**Acoustic field impacted by**

- Porous parameters by **$R_s$** and optimization
- Aerodynamic load



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# OBJECTIVES

1. Porous media configuration
   - Find a scaling law between porous parameters and surface impedance
   - Find non-dimensional parameters supporting the scaling law

2. Variable porosity
   - Impact of the optimized parameters on the acoustic field

3. Sensitivity of noise reduction
   - Impact of porous surfaces on the tone and the broadband noise
   - Impact of aerodynamic load on the noise generation:
     a zero and a finite angle-of-attack

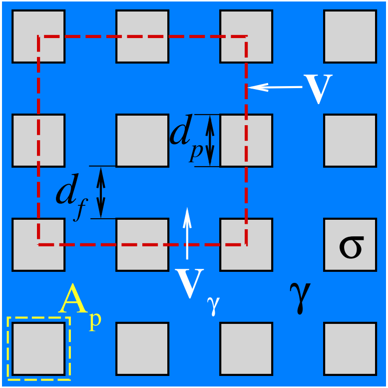
# NUMERICAL METHOD

## Flow governing equations: Volume-averaging approach*

### Porous parameters

**Homogeneous isotropic porous media**

- Porosity: $\psi = V_\gamma / V$
- Mean structure size: $d_p$
- Mean capillary size: $d_f$
- Surface filter area: $A_p$




* Whitaker, Ind. End. Chem., 61, 1969; Whitaker, Transport Porous Med., 1, 1986;
Breugem et al., J. Fluid Mech., 562, 2006; Mößner & Radespiel, Comput. Fluids, 108, 2015

# NUMERICAL METHOD

## Flow governing equations: Volume-averaging approach

### Volume-averaged transport equations

$$\frac{\partial \langle \rho \rangle^{\gamma}}{\partial t} + \nabla \cdot \left( \langle \rho \rangle^{\gamma} \langle \mathbf{u} \rangle \right) = 0$$

$$\begin{aligned}
\frac{\partial}{\partial t}\left( \langle \rho \rangle^{\gamma} \langle \mathbf{u} \rangle \right) + \nabla \cdot \left( \langle \rho \rangle^{\gamma} \langle \mathbf{u} \rangle \langle \mathbf{u} \rangle \right) &= -\nabla \langle p \rangle^{\gamma} + \nabla \cdot \tau \\
&+ \underbrace{\frac{1}{V} \int_{A_p} \left( -\mathbf{I} p + \tau \right) \mathbf{n} \, dA}_{\text{surface filter}}
\end{aligned}$$

$$\begin{aligned}
\frac{\partial \langle E \rangle^{\gamma}}{\partial t} + \nabla \cdot \left[ \left( \langle E \rangle^{\gamma} + \langle p \rangle^{\gamma} \right) \langle \mathbf{u} \rangle \right] &= \nabla \cdot \left( \tau \, \mathbf{u} + k \nabla \langle T \rangle^{\gamma} \right) \\
&+ \underbrace{\nabla \cdot \left[ \left( \mathbf{K}_C + \mathbf{K}_D \right) \cdot \nabla \langle T \rangle^{\gamma} \right]}_{\text{surface filter}}
\end{aligned}$$



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# NUMERICAL METHOD

## Flow governing equations: Volume-averaging approach

### Density weighted averaging

$$\langle \rho \rangle^V = \frac{1}{V}\int_{V_\gamma} \rho \, dV = \psi \langle \rho \rangle^\gamma \, , \qquad \langle \mathbf{u} \rangle = \frac{\langle \rho \mathbf{u} \rangle^V}{\langle \rho \rangle^V} = \frac{\langle \rho \mathbf{u} \rangle^\gamma}{\langle \rho \rangle^\gamma}$$

### Permeability and Forchheimer tensors

$$\frac{1}{V}\int_{A_p} (-\mathbf{I}p + \tau)\, \mathbf{n} dA = -\frac{\langle \mu \rangle^\gamma}{\mathbf{K}} \psi \langle \mathbf{u} \rangle - \frac{\langle \mu \rangle^\gamma}{\mathbf{K}} \psi \mathbf{F} \langle \mathbf{u} \rangle$$

$$\mathbf{K} = \frac{d_p^2 \, \psi^3}{C_K (1-\psi)^2} \mathbf{I} \, , \qquad \mathbf{F} = \frac{d_p \, \psi}{C_F (1-\psi)} \frac{\langle \rho \rangle^\gamma}{\langle \mu \rangle^\gamma} \, |\langle \mathbf{u} \rangle| \, \mathbf{I}$$

### Thermal conductivity and thermal dispersion tensor

$$\nabla \cdot \left[ (\mathbf{K}_C + \mathbf{K}_D) \cdot \nabla \langle T \rangle^\gamma \right] = -\frac{1}{K_t} (\langle T \rangle^\gamma - T_p)$$



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# NUMERICAL METHOD

## Acoustic governing equations

### Acoustic perturbation equations

⋆ The complete system of acoustic perturbation equations (APE) for the perturbation variables $(p', \mathbf{u}^a)^T$ reads

$$\frac{\partial p'}{\partial t} + \overline{c}^2 \nabla \cdot \left( \overline{\rho} \mathbf{u}^a + \overline{\mathbf{u}} \frac{p'}{\overline{c}^2} \right) = \overline{c}^2 q_c$$

$$\frac{\partial \mathbf{u}^a}{\partial t} + \nabla (\overline{\mathbf{u}} \cdot \mathbf{u}^a) + \nabla \left( \frac{p'}{\overline{\rho}} \right) = \mathbf{q}_m \ ,$$

where the acoustic sources in the right-hand side are

$$q_c = -\nabla \rho \cdot \mathbf{u}^v + \frac{\overline{\rho}}{c_p} \frac{\overline{D} s'}{Dt}$$

$$\mathbf{q}_m = \nabla \Phi_P + \nabla q_{\overline{\omega}} + T' \nabla \overline{s} - s' \nabla \overline{T}.$$

Ewert & Schröder, *J. Comput. Phys.*, 188:365–398, 2003.



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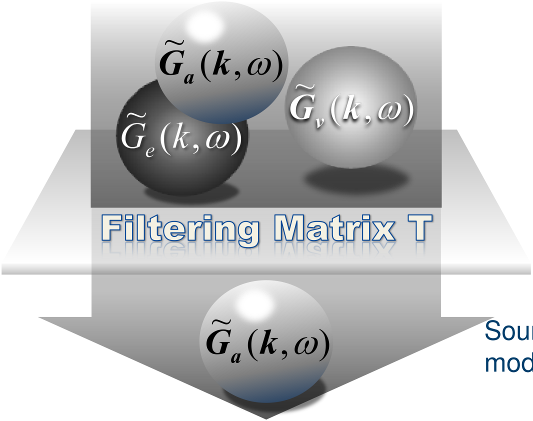
# NUMERICAL METHOD

## Acoustic source filtering

Source vector **G** represented by the Fourier-Laplace transform




$\tilde{G}_a(k,\omega)$: acoustic mode

$\tilde{G}_v(k,\omega)$: vorticity mode

$\tilde{G}_e(k,\omega)$: entropy mode

Source excites only acoustic eigen-mode $\tilde{G}_a(k,\omega)$.

Ewert & Schröder, *J. Comput. Phys.*, 188:365–398, 2003.

# NUMERICAL METHOD

- **Large-eddy simulation (LES)**
  - Volume-averaged transport equations for compressible flows
  - MILES approach (Fureby and Grinstein, *AIAA J.*, 1999)
  - 2nd order accurate modified low-dissipation AUSM scheme (Meinke et al., *Comput. Fluids*, 2002)
  - Explicit 5-stage Runge-Kutta method

- **Acoustic simulation**
  - Acoustic perturbation equations (Ewert and Schröder, *J. Comput. Phys.*, 2003)
  - 6th order DRP scheme (Tam and Webb, *J. Comput. Phys.*, 1993)
  - Alternating 5-6 stage low-dissipation low-dispersion Runge-Kutta method (Hu et al., *J. Comput. Phys.*, 1996)
  - High order explicit low-pass filtering (Bogey and Bailly, *J. Comput. Phys.*, 2004)
  - Radiation boundary condition (Tam and Webb, *J. Comput. Phys.*, 1993)



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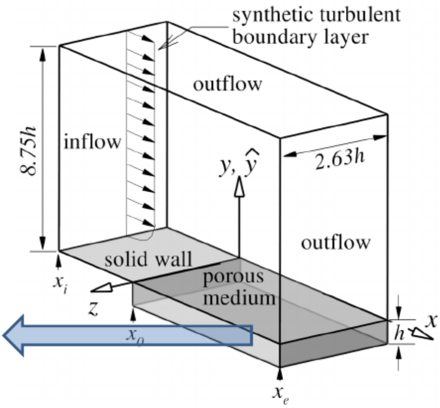
# POROUS PARAMETERS

## Correlation with flow variables

- $Re_{\delta*} = 1280$ at the inflow boundary
- Streamwise extent: $L_x = 37.5h\ (150\delta^*)$
- $\Delta x^+ = 15$, $\Delta y^+ = 0.8$ , $\Delta z^+ = 7.5$

- Porous medium thickness: $h = 4\delta^*$

| ψ (porosity) | $d^+_p$ (micro-structure size) |
|---|---|
| 0.3 | 3.5 |
| 0.5 | 3.5 |
| 0.5 | 8.75 |
| 0.5 | 17.5 |
| 0.5 | 35 |
| 0.7 | 3.5 |
| 0.9 | 3.5 |



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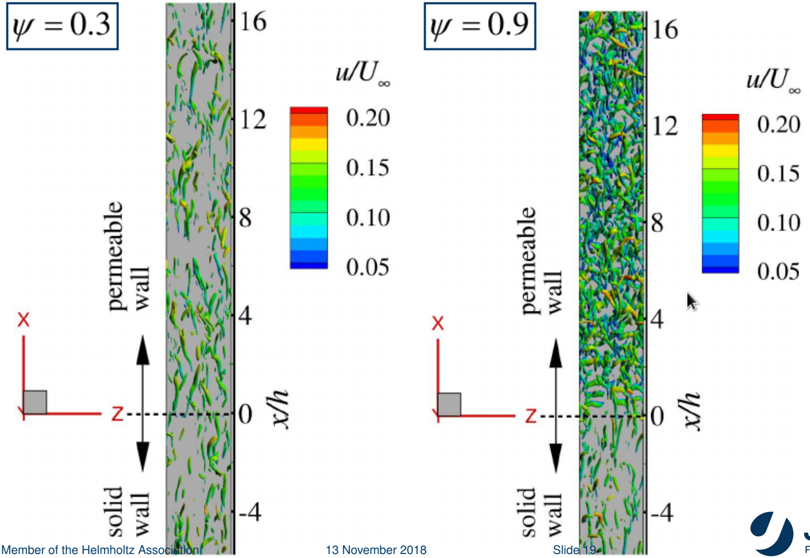
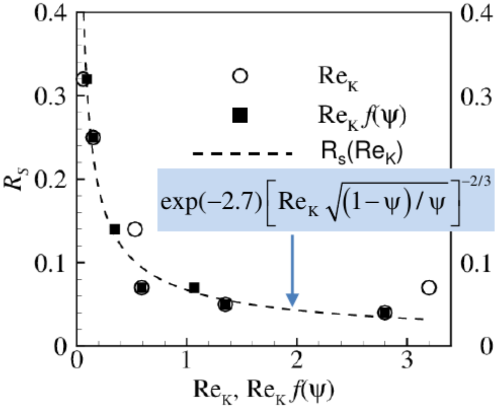


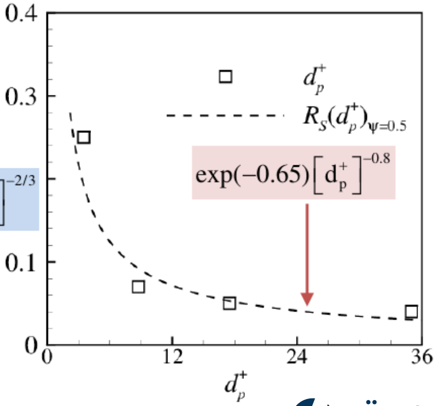
# POROUS PARAMETERS

## Correlation with flow variables

Koh et al., *J. Sound Vib.*, 421:348–376, 2018.

$$\mathrm{Re}_K = \sqrt{K} u_{\tau,p} / \nu, \qquad R_s = \frac{1}{\rho_\infty a_\infty} \sqrt{\frac{(p'_a)^2 - (p'_b)^2}{(v'_a)^2}}$$



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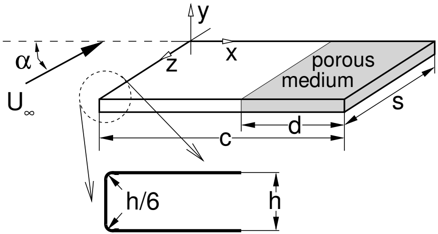
# FLOW CONFIGURATION

## Trailing-edge setup




- Flat plate with a finite thickness
  $Re_c = 135,000$, $Ma = 0.06$
  $U_\infty$: freestream velocity (20m/s)
- $h$: plate thickness ($= 0.03c$)
  $d$: porous medium length ($= 0.12c$)
  $s$: span size ($= 3c$)

# FLOW CONFIGURATION

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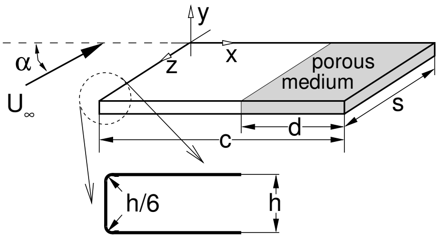


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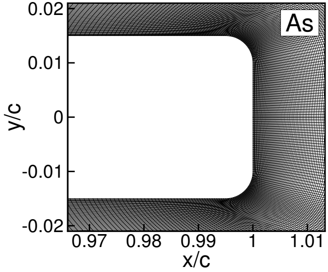
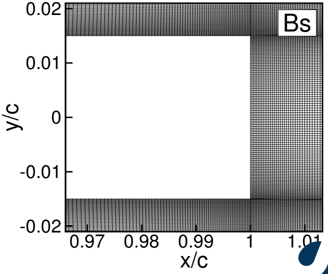
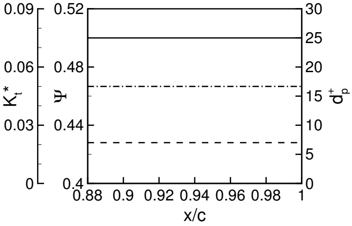


# FLOW CONFIGURATION

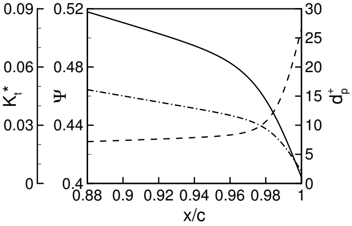
## Porous structure setup

**constant porosity denoted by 'p'**




**TBL** (Koh et al., J. Sound Vib., 2018)

**variable porosity denoted by 'v'**

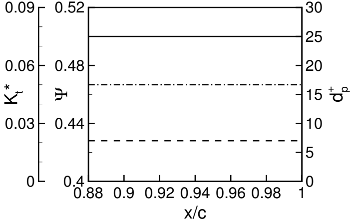



**optimization** (Koh et al., Comput. Fluids, 2018)

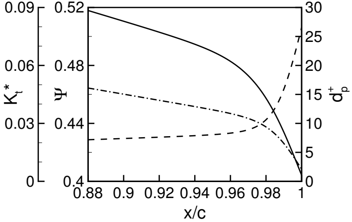
# FLOW CONFIGURATION

## Porous structure setup

**constant porosity denoted by ‘p’**




**variable porosity denoted by ‘v’**




| configuration | AoA $\alpha$(deg) | porosity $\psi$ | mean particle diameter $d_p^+$ | thermal permeability $K_t^*$ |
|---|---|---|---|---|
| As | 0 | - | - | - |
| Ap | 0 | 0.5 | 7 | 0.05 |
| Bs | 0 | - | - | - |
| Bp | 0 | 0.5 | 7 | 0.05 |
| Bv | 0 | 0.4–0.52 | 7–26.5 | 0.006–0.048 |

# FLOW CONFIGURATION

## Porous structure setup

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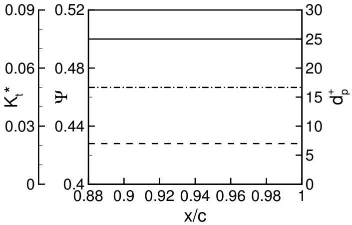
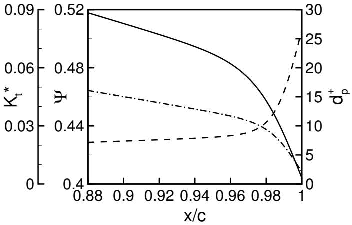



**variable porosity denoted by 'v'**




| configuration | AoA $\alpha$(deg) | porosity $\psi$ | mean particle diameter $d_p^+$ | thermal permeability $K_t^*$ |
|---|---|---|---|---|
| As | 0 | - | - | - |
| Ap | 0 | 0.5 | 7 | 0.05 |
| Bs | 0 | - | - | - |
| Bp | 0 | 0.5 | 7 | 0.05 |
| Bv | 0 | 0.4–0.52 | 7–26.5 | 0.006–0.048 |
| As2 | 2 | - | - | - |
| Ap2 | 2 | 0.5 | 7 | 0.05 |
| Av2 | 2 | 0.4–0.52 | 7–26.5 | 0.006–0.048 |



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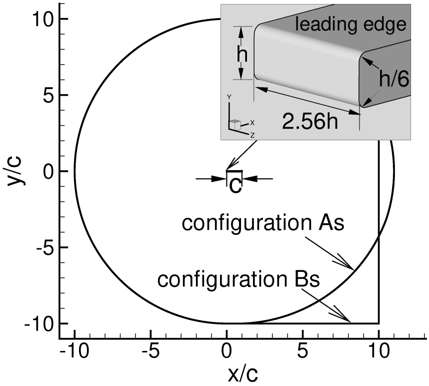
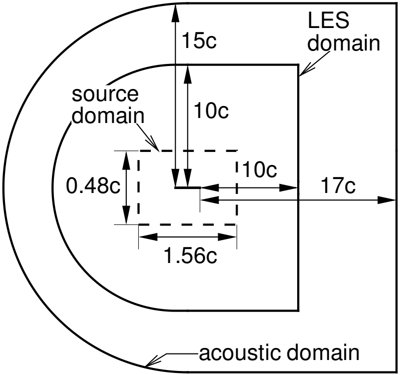
# FLOW CONFIGURATION

## Computational domain



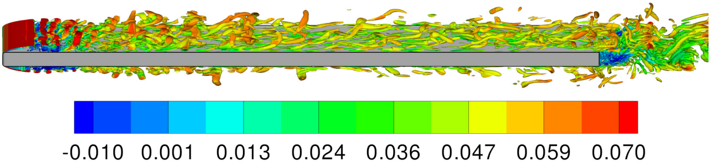

**LES domain**



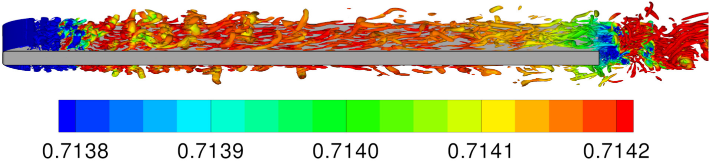

**CAA domain**

# RESULTS AT ZERO AOA

## Second invariant of velocity gradient tensor at $Q = 1.0 a_\infty^2 / c^2$




**streamwise velocity** $u/a_\infty$




**static pressure** $p/\rho_\infty a_\infty^2$



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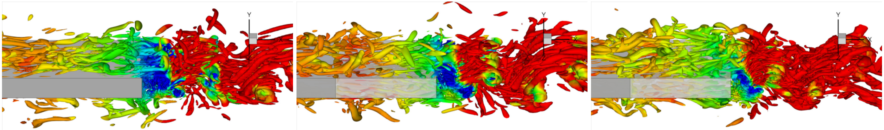
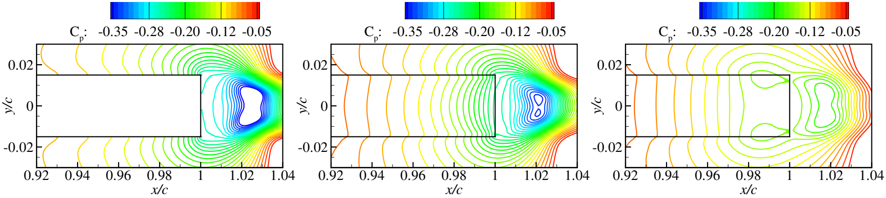
# RESULTS AT ZERO AOA

## Static pressure contours near the trailing edge

**Bs** **Bp** **Bv**



**static pressure $p/\rho_\infty a_\infty^2$**




**mean static pressure coefficient ($C_p$)**



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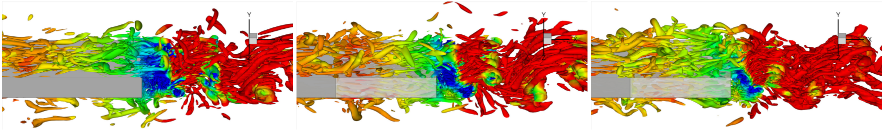
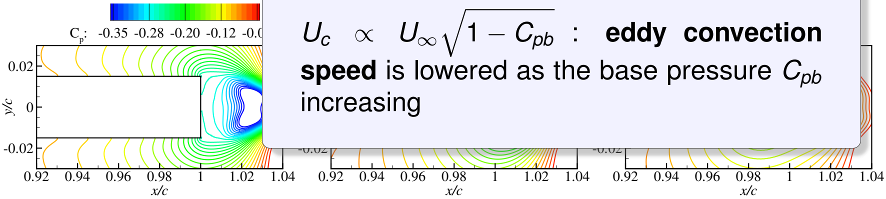
# RESULTS AT ZERO AOA

## Static pressure contours near the trailing edge

**Bs** **Bp** **Bv**






### Convection speed

$U_c \propto U_\infty \sqrt{1 - C_{pb}}$ : **eddy convection speed** is lowered as the base pressure $C_{pb}$ increasing

**mean static pressure coefficient ($C_p$)**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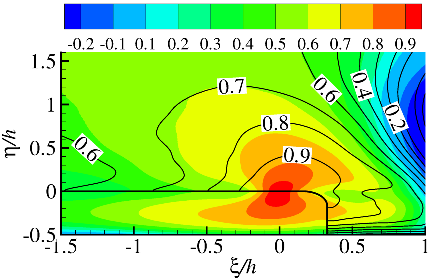
# RESULTS AT ZERO AOA

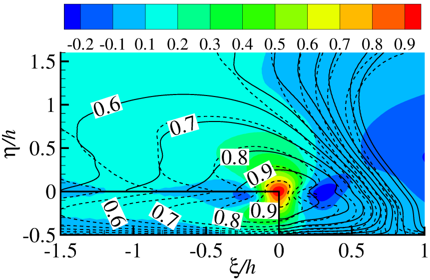
## Two-point correlation of pressure fluctuations near the trailing edge ($\xi\eta$-plane, streamwise/wall normal distance)

**TE shape A**




As (——); Ap (color)

**TE shape B**




Bs (——); Bp (— — —); Bv (color)



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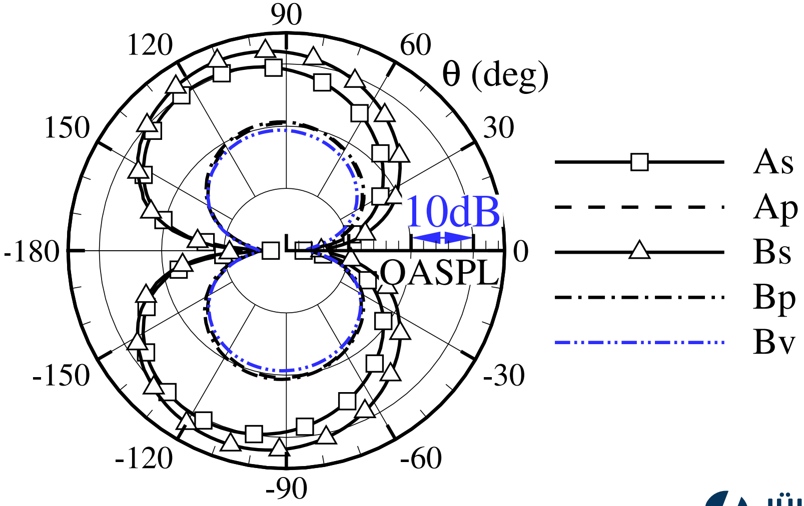
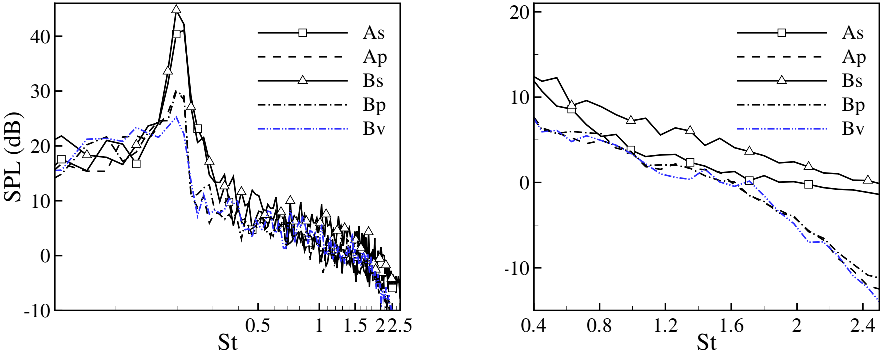
# RESULTS AT ZERO AOA

## Overall sound pressure level



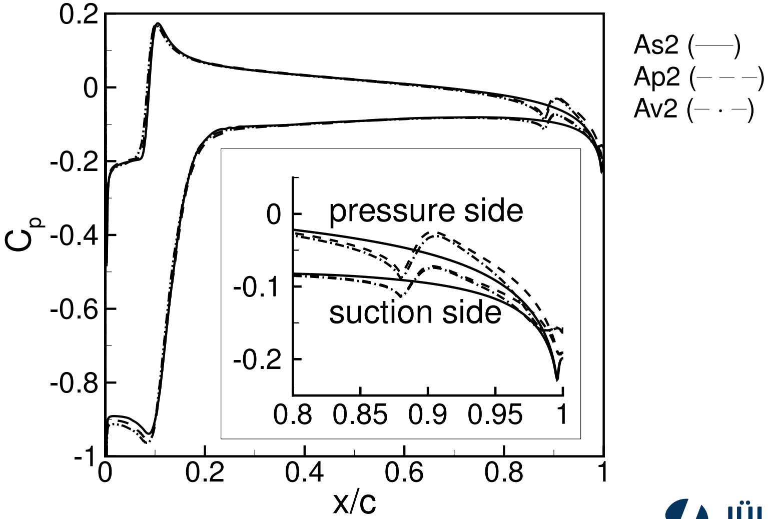
# RESULTS AT ZERO AOA

## Sound spectra at the coordinates x/c = 1 and y/c = ±8 ($\theta = \pm 90°$)



# RESULTS AT 2° AOA

## Surface pressure coefficient ($C_p$)



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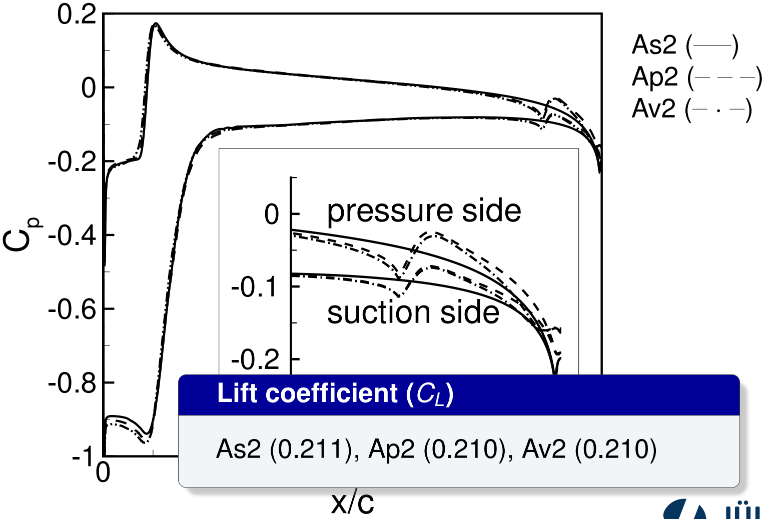
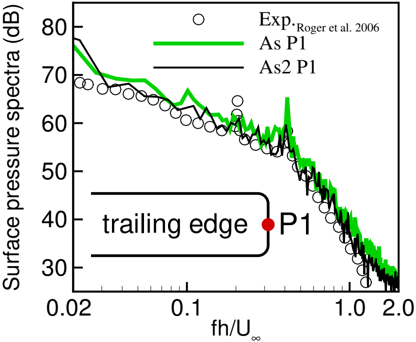


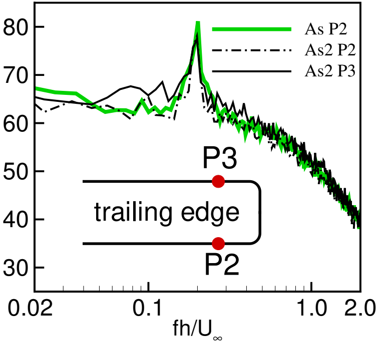

**Lift coefficient ($C_L$)**

As2 (0.211), Ap2 (0.210), Av2 (0.210)

# RESULTS AT 2° AOA

## Power spectral density of surface pressure fluctuations



# RESULTS AT 2° AOA

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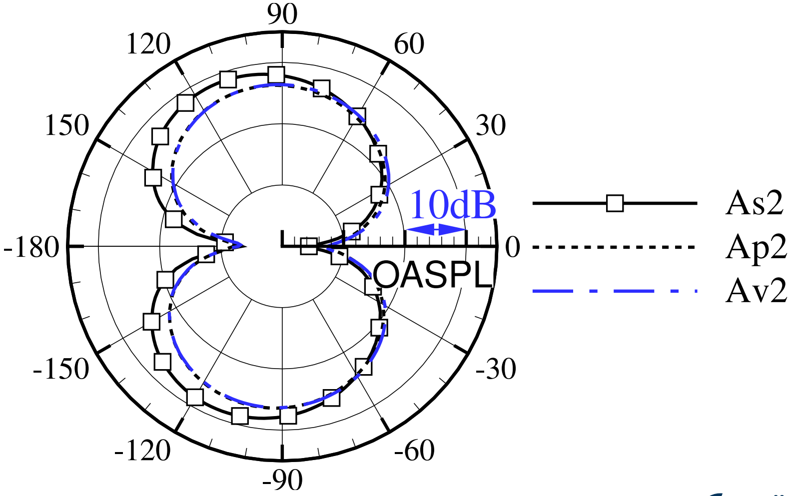




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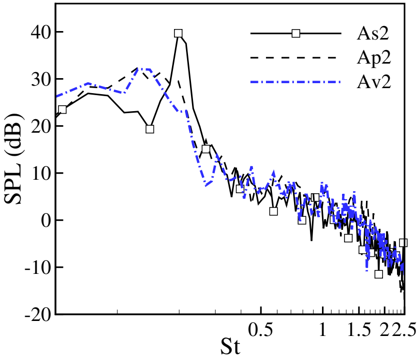
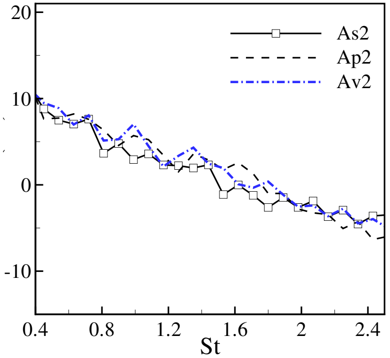
# RESULTS AT 2° AOA

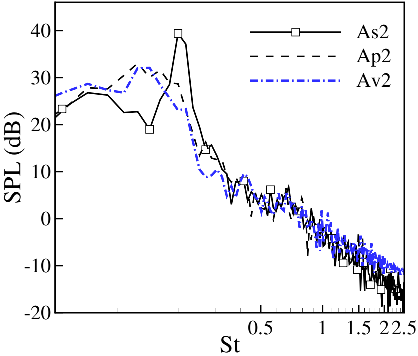
## Sound spectra at the coordinates x/c=1 and y/c=8 ($\theta = +90^{\circ}$)



# RESULTS AT 2° AOA

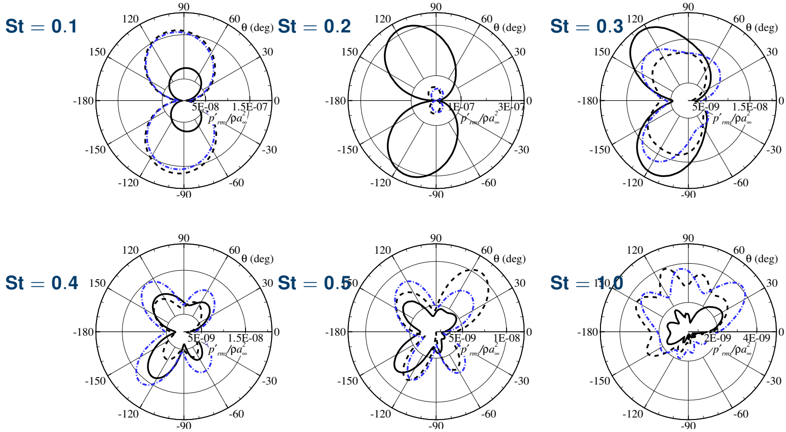
## Sound spectra at the coordinates x/c=1 and y/c=-8 ($\theta = -90°$)



# RESULTS AT 2° AOA

## Directivity

**As2 (——); Ap2 (– – –); Av2 (– · –)**



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# SUMMARY

- **Trailing-edge noise reduction via porous media**
  - A hybrid LES/CAA approach is used to analyze the impact of porous media parameters on the flow and the acoustic field.
  - Baseline porous parameters ($\psi$, $Re_d$, $Re_K$) minimizing the flow resistance ($R_s$).

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  - Optimized distribution obtain an additional tonal noise reduction.

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- **Variable porosity at a finite angle-of-attack**
  - No additional acoustic reduction via the variable porosity distribution.
  - In future optimization approaches the angle-of-attack should be considered an optimization parameter.


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