Analysis of the non-linear behavior of micro-perforated plates using lattice Boltzmann method

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Introduction

- The **linear acoustic behavior** of micro-perforated plates is **well understood**.
- The **non-linear behavior** under high sound pressure level (or submitted to a flow) has been studied but the models are **still limited**.
- The idea of this work is to analyse this non linear behavior at the **microscopic scale** using the **lattice Boltzmann method** (LBM) to improve analytical models.

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Modeling the linear behavior of micro-perforated plates

- Numerous analytical models can be found in the literature for modeling the linear behavior of micro-perforated plates :

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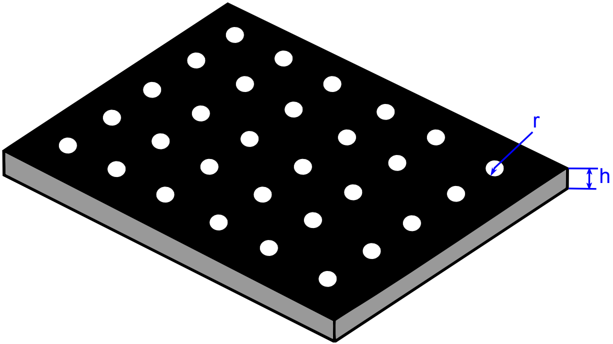
Modeling the linear behavior of micro-perforated plates

- These models are based on the **same parameters** :
  r : perforation radius, ϕ : perforation rate, h : plate thickness
- and generally differ in the way to take into account the **flow distorsion** (resistance and reactance corrections)



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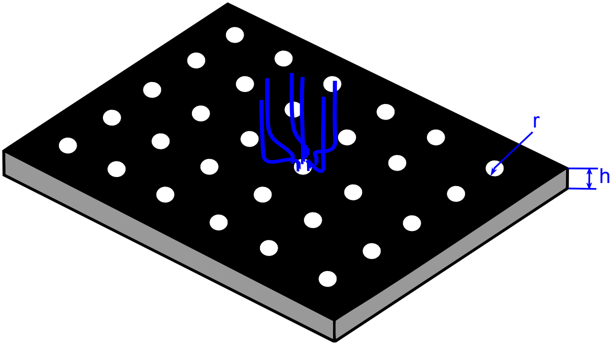

Example of impedance models

- Maa's model (1998) :

$$\tilde{Z}_s = \frac{32\eta h}{\phi d^2}\left(\sqrt{1+\frac{k^2}{32}}+\frac{\sqrt{2}}{32}k\frac{d}{h}\right)+j\omega\frac{\rho_0 h}{\phi}\left[\left(1+\frac{1}{\sqrt{9+\frac{k^2}{2}}}\right)+0.85\frac{d}{h}\right]+Z_B$$

$d = 2r$, $R_s = \frac{1}{2}\sqrt{2\eta\omega\rho_0}$ and $k = \frac{2r}{\sqrt{2}\eta}R_s$, Z_B : backing impedance

- Guo's model (2008) :

$$\tilde{Z}_s = \frac{j\rho_O\omega h}{\phi}\left[1-\frac{2}{k\sqrt{-j}}\frac{J_1\left(k\sqrt{-j}\right)}{J_0\left(k\sqrt{-j}\right)}\right]^{-1}+\frac{\alpha 2R_s}{\phi}+j\omega\rho_0\frac{\delta}{\phi}+Z_B \quad (1)$$

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Modeling a perforated plate as a porous medium

- A **perforated plate** may be viewed as a **porous material**.
- **Macroscopic parameters using the 5-parameter JCA model :**

  ϕ : perforation rate

  $$\Lambda = \Lambda' = r$$

  $$\sigma = \frac{8\eta}{\phi r^2}$$

  $$\alpha_\infty = 1 + \frac{n\epsilon}{h}$$

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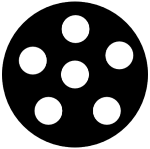
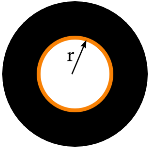




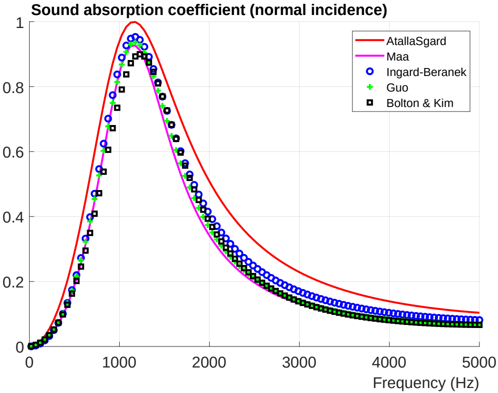
h : Thickness of the plate

ϵ : Length correction

n : Factor depending on the nature of upstream and downstream materials

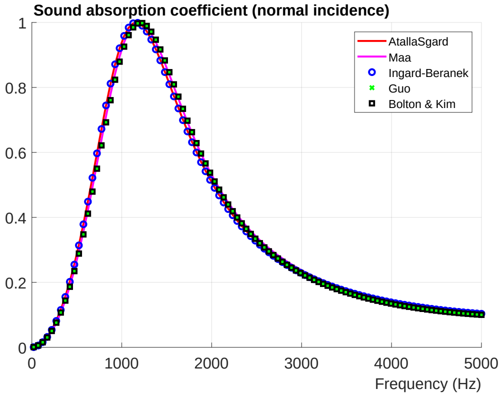
Modeling the linear behavior of micro-perforated plates

- Comparison of linear models using **original corrections**.



$\phi = 0.025$, $h = 1\ mm$, $d = 1\ mm$, $L_c = 20\ mm$, glasswhool $\sigma \approx 10\,000\ N.s.m^{-4}$

- Comparison of linear models using the **same correction.**



ϵ can be computed for any shape of perforation in the full range of porosity [0-1].

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Non-linear regime behavior

- Melling has studied this non-linear effect for perforated plates submitted to a high sound pressure level :

$$R_t = R_{lin}\left(L_p\right) + \frac{\rho_0}{2}\frac{8}{3\pi}\frac{1}{C_d^2}\frac{1-\phi^2}{\phi^2}U$$

with $R_t = \sigma_t L_p$ the airflow resistance,

- The **non-linear term** is proportional to the **velocity level** U and depends on the **open porosity** ϕ and a **discharge coefficient** C_d.
- C_d is generally obtained from experiments.

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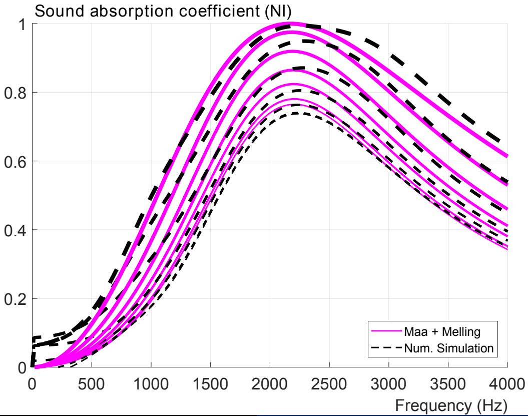
Non-linear regime behavior

- Melling's model **does** predict the shift in amplitude with SPL,
- but **does not** predict the shift in frequency with SPL,
- and requires a **discharge coefficient** C_d.



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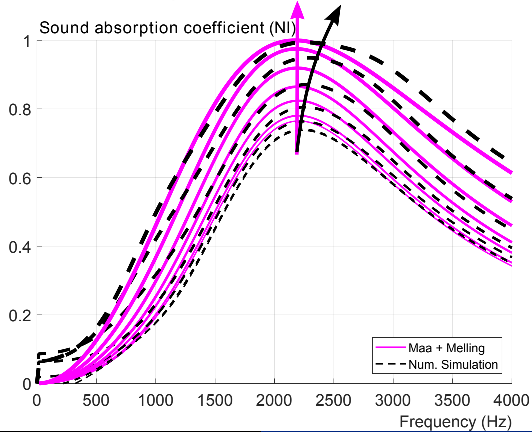

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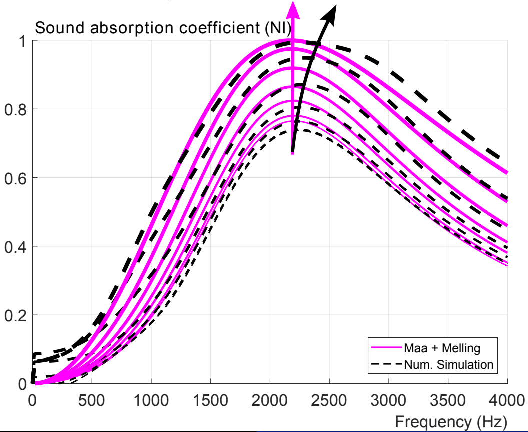
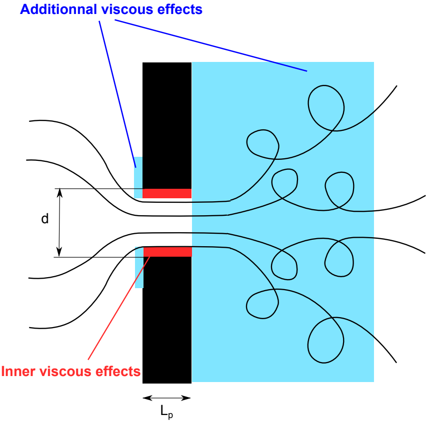
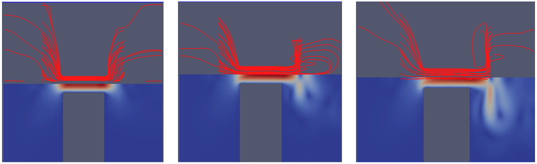


Analysis at the microscopic level

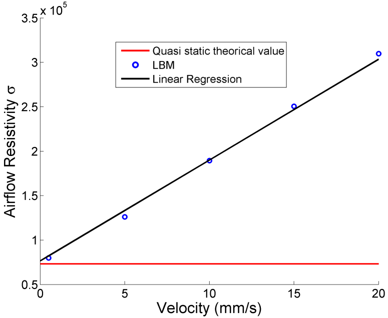


$$R_t\left(\phi, L_p, U, d\right) = R_p\left(\phi, L_p, U, d\right) + R_r\left(\phi, U\right)$$

Modeling from the microstructure



a) $U = 0.5\ mm.s^{-1}$ b) $U = 5\ mm.s^{-1}$ c) $U = 10\ mm.s^{-1}$



Analysis at the microscopic level

- The total resistance is the sum of the **inner** viscous effects R_p and the **addditional viscous effects** R_r :

$$R_t\left(\phi, L_p, U, d\right) = R_p\left(\phi, L_p, U, d\right) + R_r\left(\phi, U\right)$$

- The inner resistance R_p is proportional to the airflow resistivity σ_p :

$$R_t\left(\phi, L_p, U, d\right) = \sigma_p\left(\phi, U, d\right) L_p + R_r\left(\phi, U\right)$$

- Both the inner and the additional viscous effects may have a non linear behavior :

$$R_t\left(\phi, L_p, U, d\right) = \left(\sigma_{p0} + \sigma_{pi}|U|\right) L_p + R_{r0} + R_{ri}|U|$$

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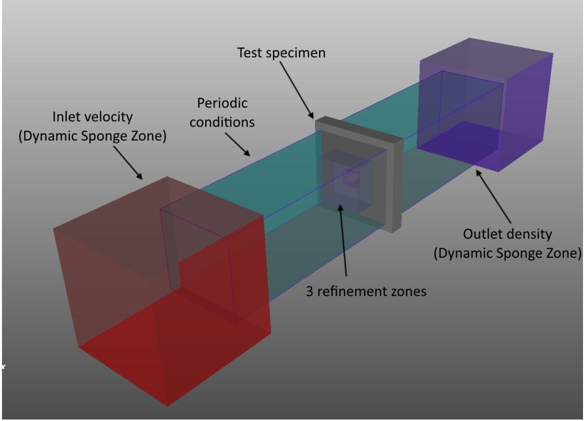
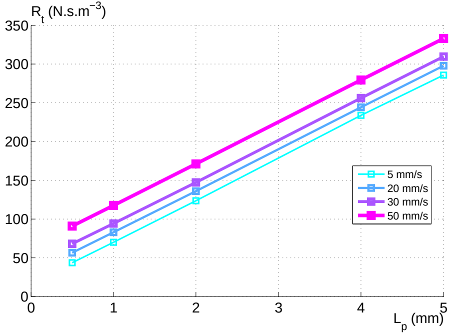
- A parametric study has been carried out in order to determine these coefficients.
  - Perforation thickness $L_p \in [0.5 - 5 \text{ mm}]$
  - Perforation diameter $d \in [0.5 - 4 \text{ mm}]$
  - Perforation rate $\phi \in [0.0314 - 0.503]$.



Airflow resistance determination

- Airflow resistance as a function of the perforation thickness for 4 upstream velocity levels :



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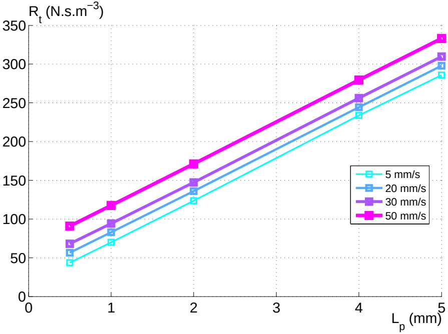

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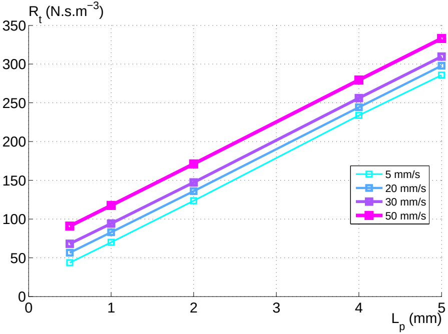

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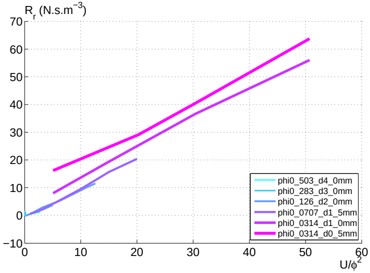
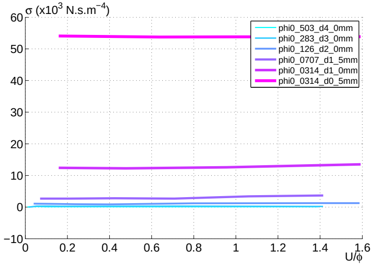
Airflow resistance determination

- Extraction of R_r and σ_p :





- The inner effects σ_p do not show a non-linear behavior for this range of upstream velocity.
- The **non-linear behavior** strongly depends on the **downstream flow distorsion** and seems proportional to U/ϕ^2 (as Melling's non-linear term).
- **Numerical methodology** to determine the **discharge coefficient** C_d.

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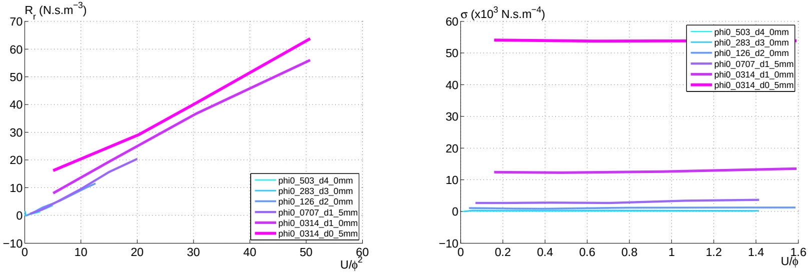

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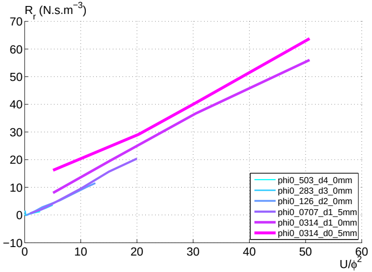

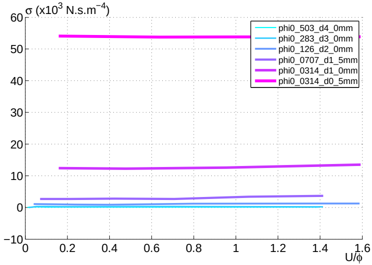

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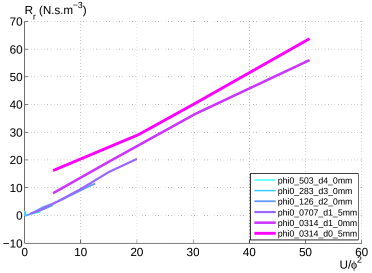

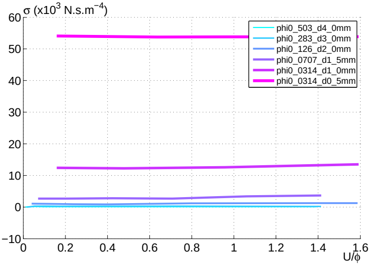

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Proposed non-linear model

- **Macroscopic parameters using the 5-parameter JCA model :**

  - From geometrical parameters :

    ϕ : perforation rate

    $\Lambda = \Lambda' = r$ (Λ is computed for a perfect non-viscous fluid)

  - Correction of low frequency viscous effect :

    $$\sigma = \frac{8\eta}{\phi r^2} + \frac{R_r}{L}$$

  - Inertial effect (length correction) :

    $$\alpha_\infty = 1 + \frac{n\epsilon}{L}$$

    ϵ can be computed for any shape of perforation in the full range of porosity [0-1].

- The 5-parameter JCA model enables to **independently control the low and high frequency asymptotic behaviors**.

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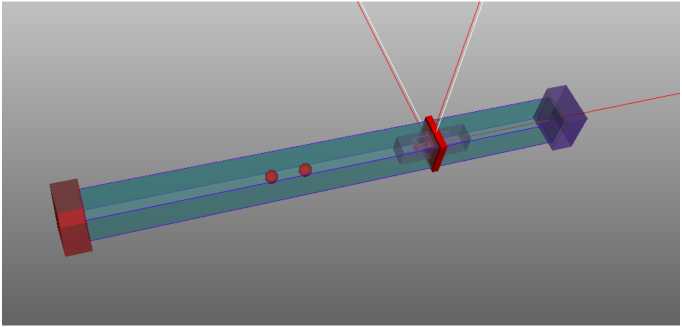
Dynamic simulation under high SPL using LBM



- Perforated plate submitted to a dynamic excitation,
- Considered excitations :
  - Pulse : wide frequency band without control of the overall level,
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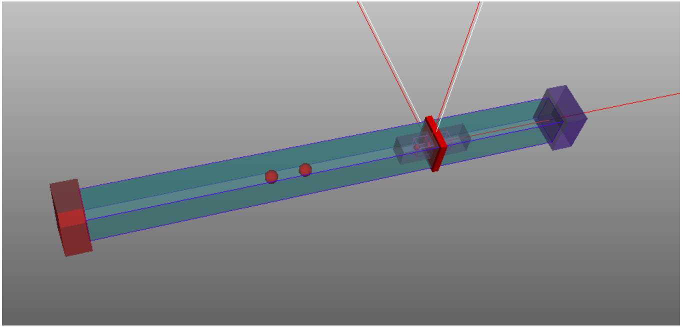

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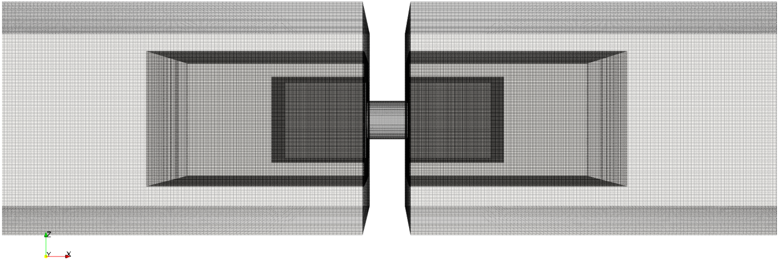
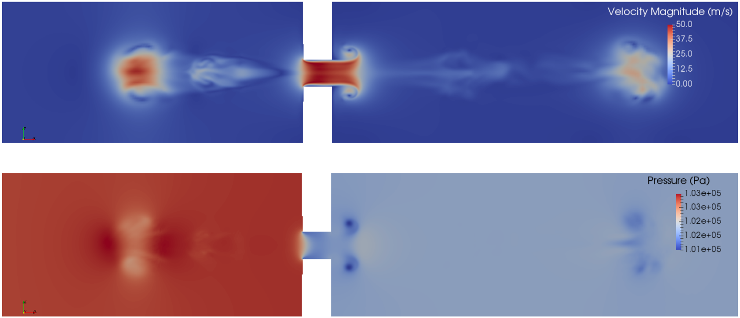
  - Chirp : wide frequency band with control of the overall level.

Mesh around aperture



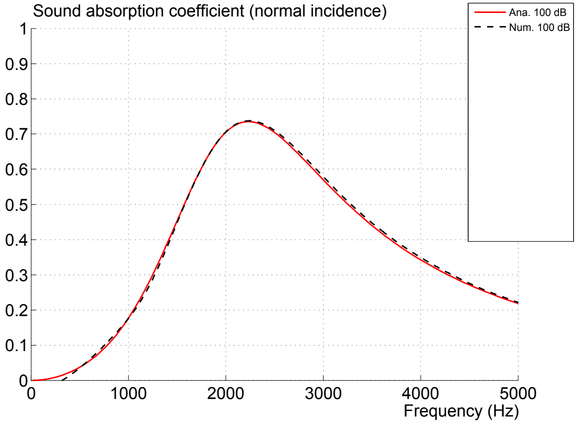
Dynamic simulation under high SPL using LBM



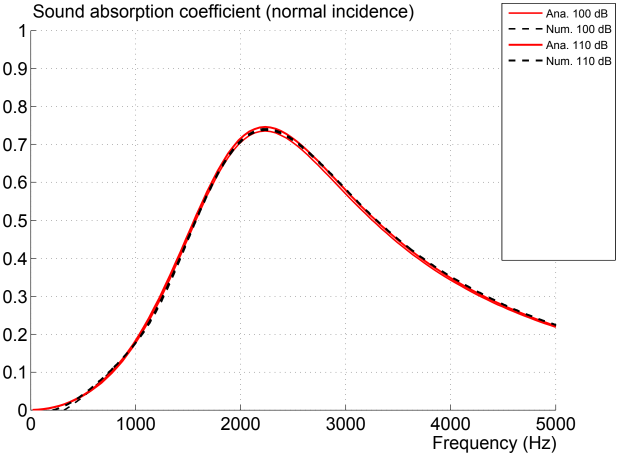
Simulation with a sine excitation at 151 dB.

Effect of the sound pressure level on the sound absorption coefficient

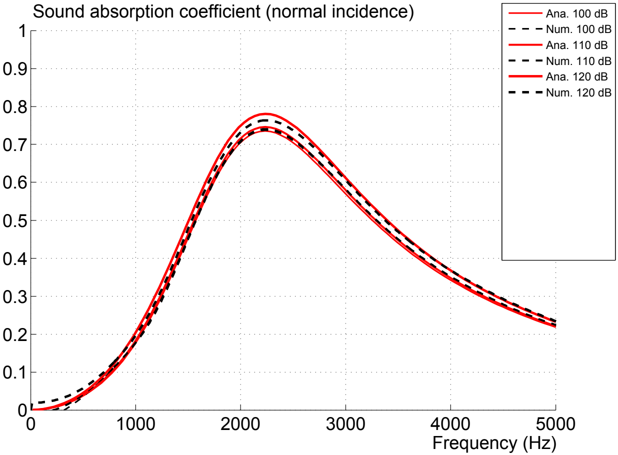
$\phi = 0.05,\ d = 0.3\ mm,\ h = 0.8\ mm$



Effect of the sound pressure level on the sound absorption coefficient



Effect of the sound pressure level on the sound absorption coefficient



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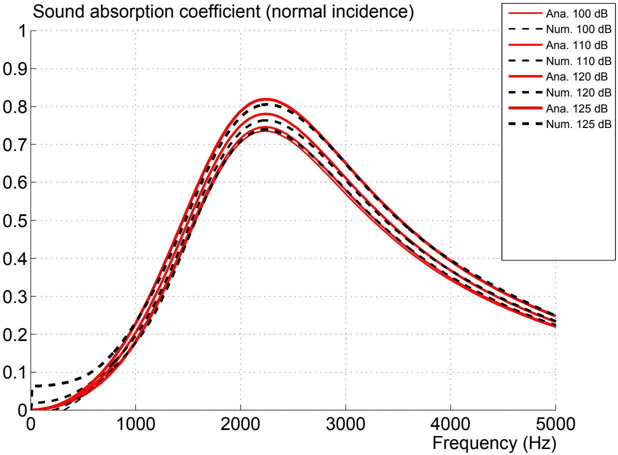

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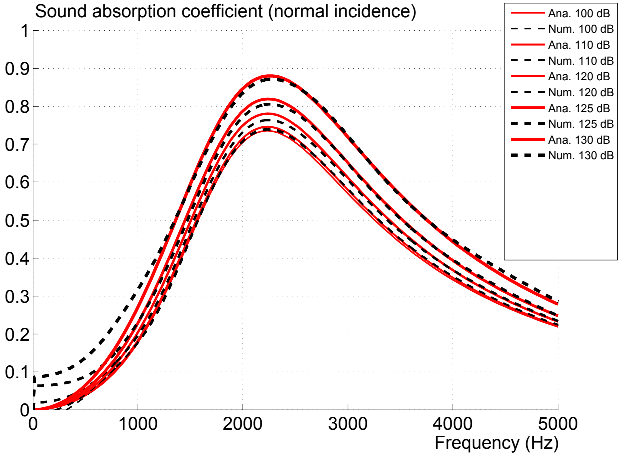

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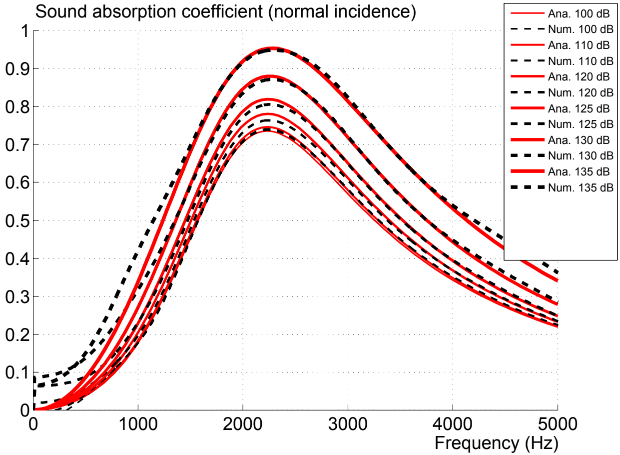

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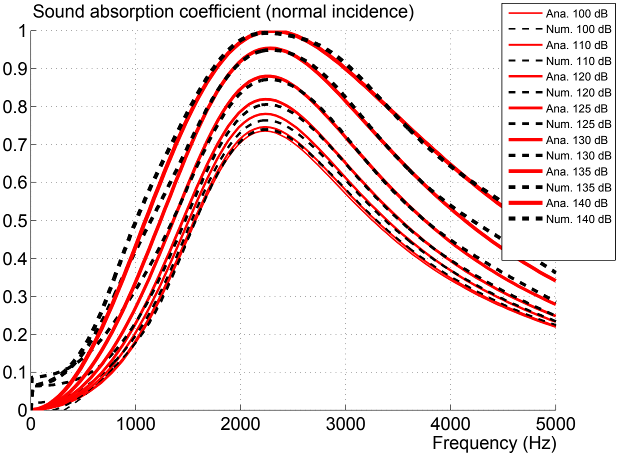

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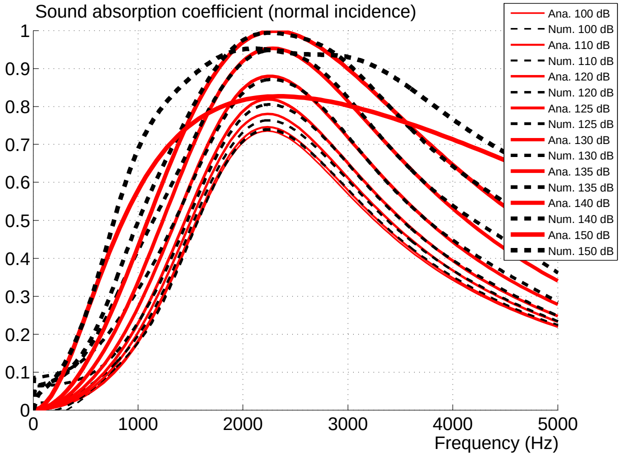
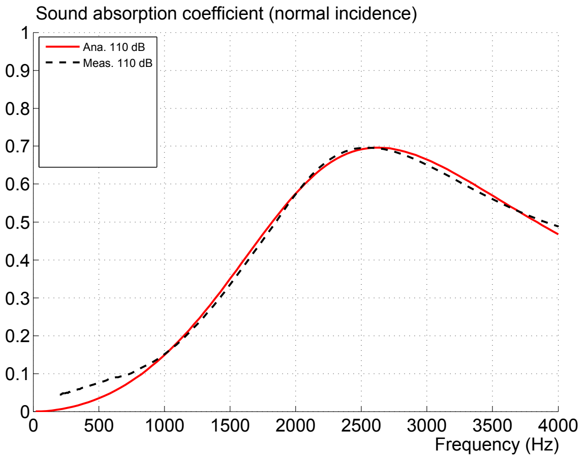
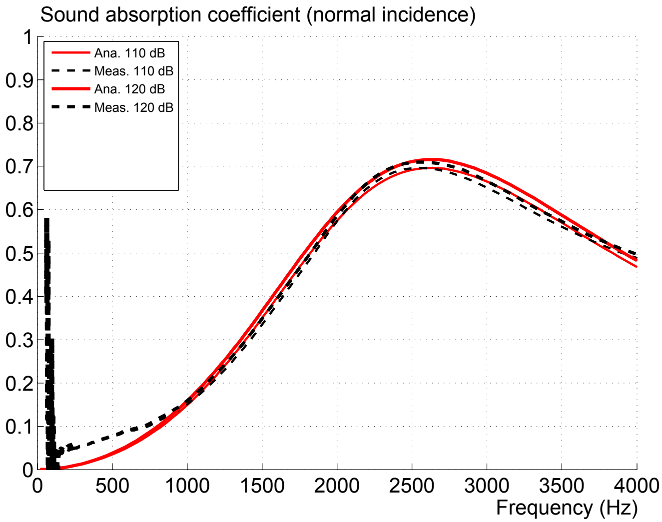
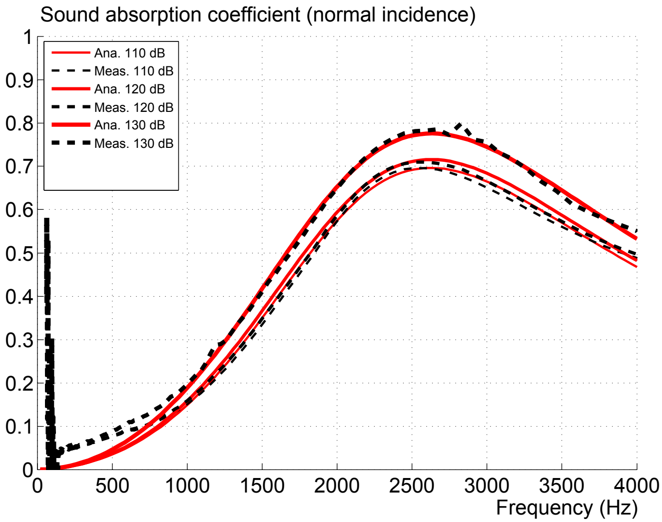
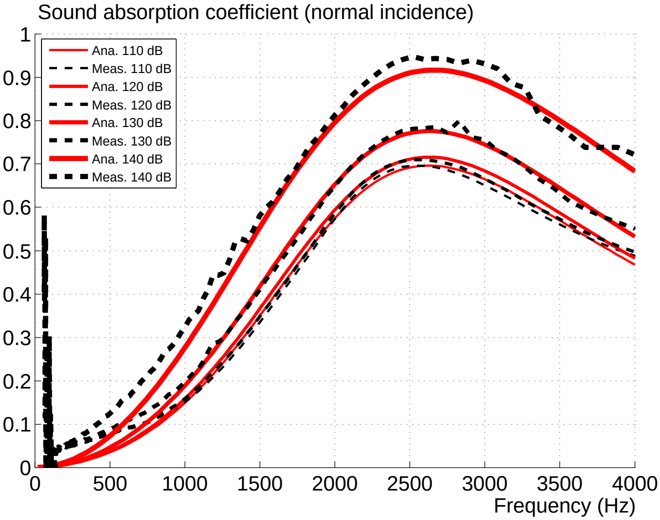


- Parameters have been estimated from the linear behavior : $\phi = 0.075$, $d = 0.25\ mm$, $h = 0.8\ mm$, $L_c = 20\ mm$;




Sound absorption coefficient (normal incidence)
Ana. 110 dB
Meas. 110 dB
Ana. 120 dB
Meas. 120 dB
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
500
1000
1500
2000
2500
3000
3500
4000
Frequency (Hz)


Sound absorption coefficient (normal incidence)
Ana. 110 dB
Meas. 110 dB
Ana. 120 dB
Meas. 120 dB
Ana. 130 dB
Meas. 130 dB
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
500
1000
1500
2000
2500
3000
3500
4000
Frequency (Hz)


Sound absorption coefficient (normal incidence)
Ana. 110 dB
Meas. 110 dB
Ana. 120 dB
Meas. 120 dB
Ana. 130 dB
Meas. 130 dB
Ana. 140 dB
Meas. 140 dB
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
500
1000
1500
2000
2500
3000
3500
4000
Frequency (Hz)

Conclusion

- The non-linear behavior of perforated plates has been studied thanks to LBM simulations.
- The non-linear resistance introduced by Melling seems to be confirmed.
- Airflow resistivity and discharge coefficient can be obtained by simulation at the microscopic level.
- The 5-parameter JCA model enables to independently control the low and high frequency asymptotic behaviors.
- The shifts in amplitude and frequency seem to be correctly predicted.
- Futher configurations have to be studied.

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Thank You For Your Attention !