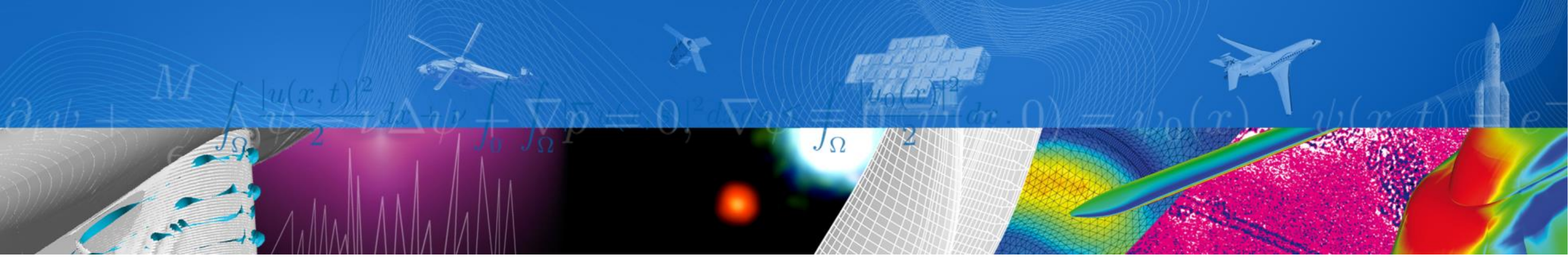

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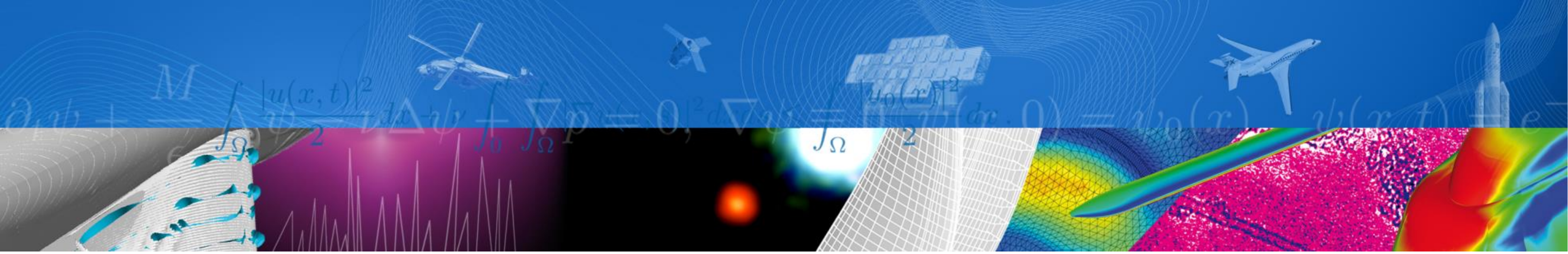

# Advanced identification techniques and design tools applied to innovative aeroacoustic liners


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**Université de Toulouse**

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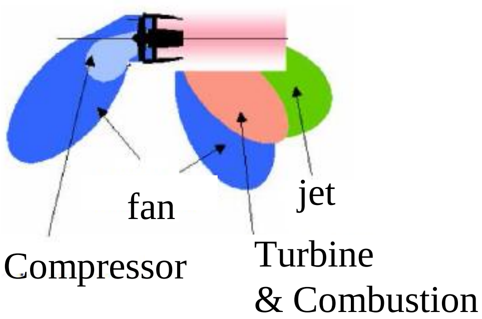
# Outline

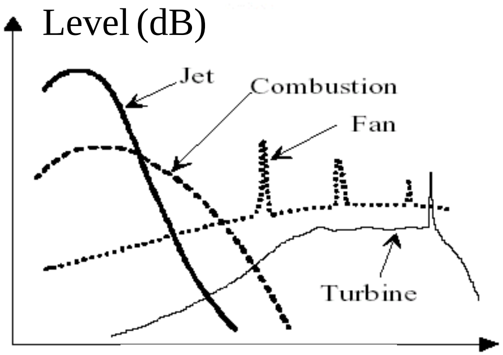
- **Context**
- **Liner design strategy**
- **Uncertainty quantification**
- **Illustration on recent ONERA activities**

# Context

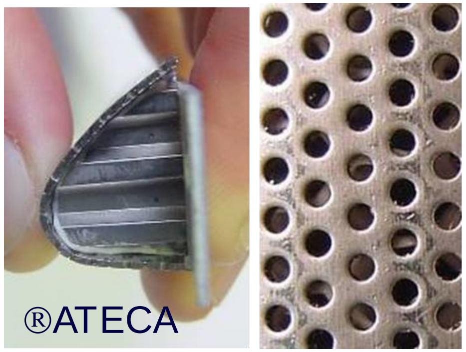
## Use of liners in nacelle of aircraft engines to reduce fan, turbine and combustion noise

zero-spliced liners - A380
(Journal Aerospace Lab (7) 2014)




## Use of liners in wing leading edge to reduce interaction noise

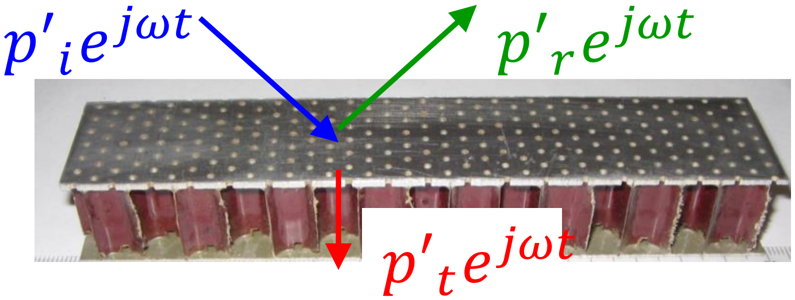



## Use of liners along a duct to reduce jet pump noise

Aircraft air conditioning

# Context

## Classical liners concepts



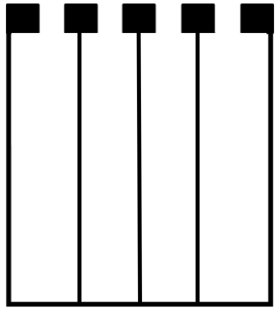

**Locally reacting** behavior

Surface **impedance**: $$Z(\omega) = \frac{p'}{\boldsymbol{v}'.\boldsymbol{n}}$$

$$Z(\omega) = R(\omega) + jX(\omega)$$

- Single Degree of Freedom liner (**SDOF**):

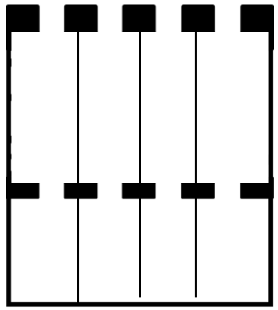
1 resistive layer (~porous) above 1 cavity (reactive)



➔ Absorption in a narrow frequency band

- Double Degree of Freedom liner (**DDOF**):

2 resistive layers and 2 cavities





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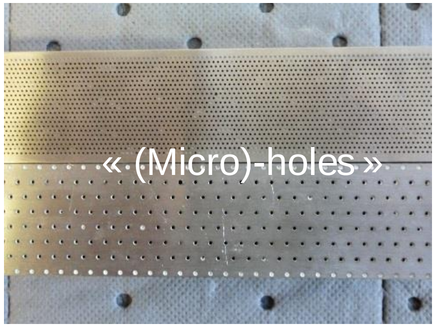
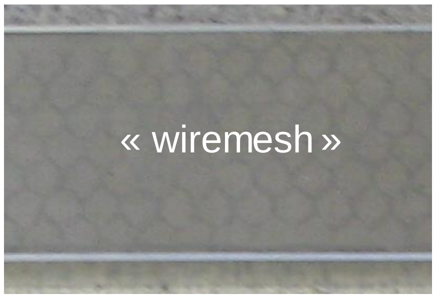
# Context

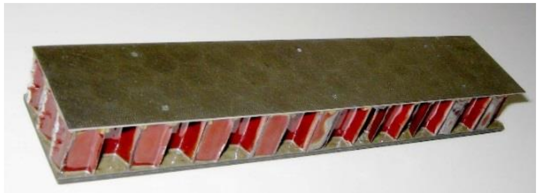




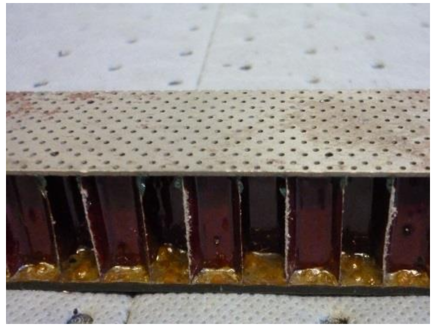


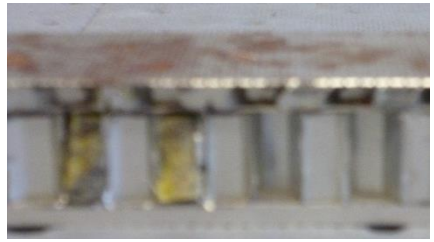

Resistive layers

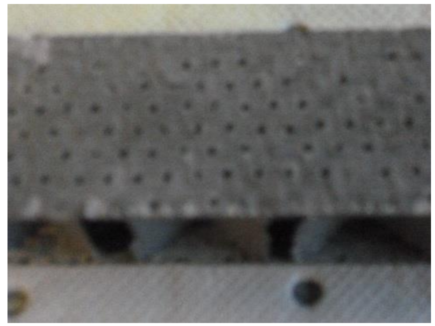
SDOF



2DOF



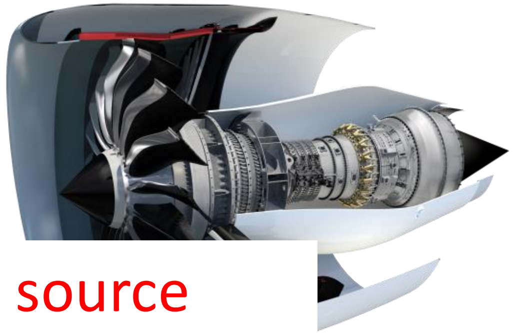


Honeycomb cells

# Context

## New challenges for noise mitigation with acoustic liners

UHBR engines



Engines

Broadband, low frequency noise source

Limited space available for liner installation

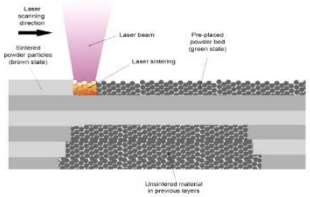
Urban air-taxi


Distributed Electrical Propulsion

# Game-changer in manufacturing process: “3D printing”

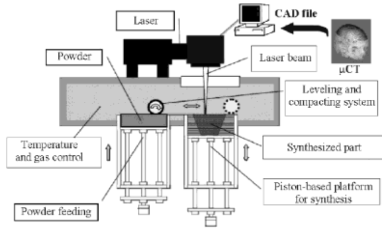
- **Sintering**

creating a solid mass using heat without liquefying it. Metal powders (DMLS) or thermoplastic powders (SLS)



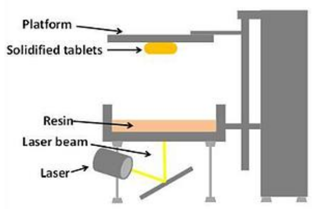

- **Direct Metal Laser Melting (DMLM) and Electron Beam Melting (EBM)**

fully melting of materials through laser or electron beam. Ideal for manufacturing dense, non-porous objects.




- **Stereolithography (SLA)**

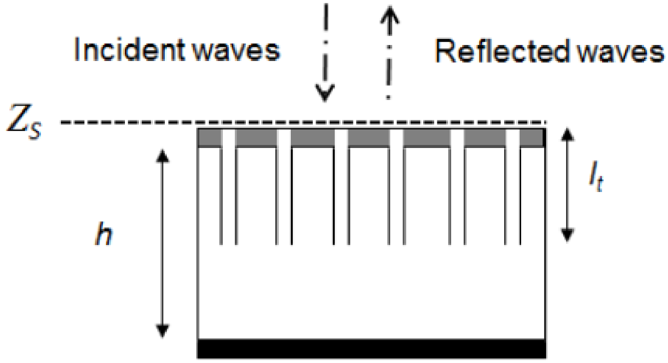
photopolymerization to print ceramic or polymer objects

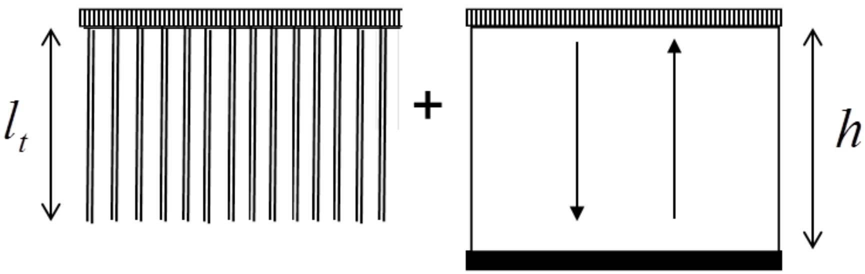


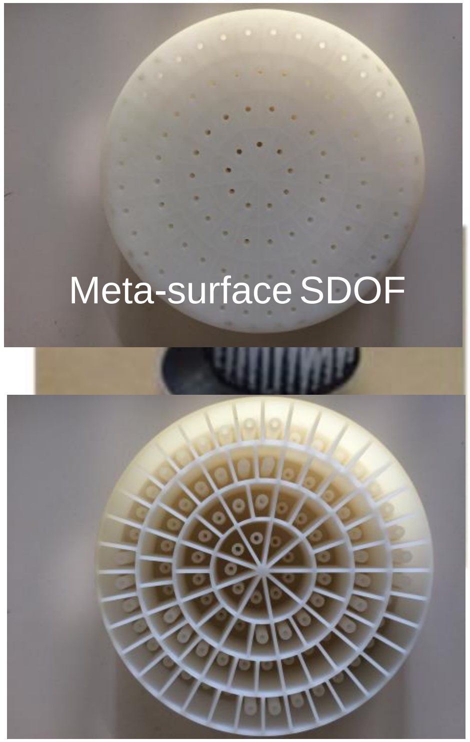

**Radical opening of the design-space for acoustic liner concepts**

# Context

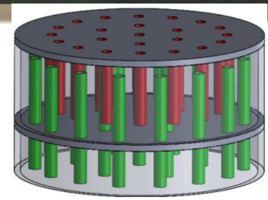
## Innovative liner concepts







2DOF

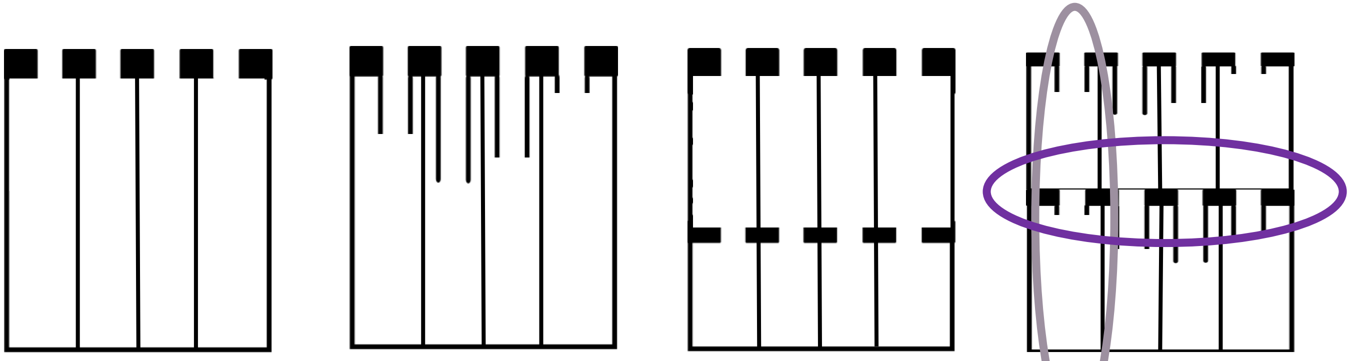
**LEONAR concept:**

- Radical decrease of the resonance frequency through the prolongation of propagation length (effect on reactance)
- Increase of the absorption coefficient at low frequencies by prolongation of tube length (added resistance)

Ref: Simon et al in ICA 2013 / Inter.noise 2016 / ICSV24 / Inter.noise 2018 /J. Sound Vib., 421, 1-16, (2018)

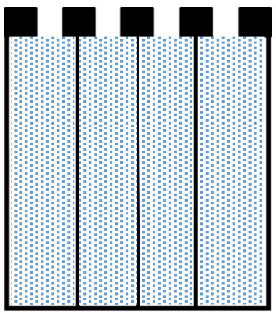
# Context

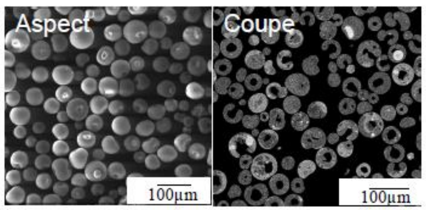
## Innovative combination of concepts

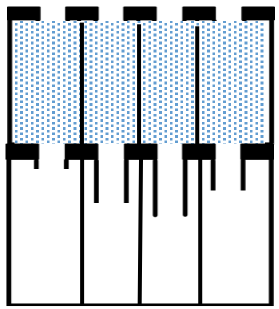



**1.** S-DOF **2.** N-DOF LEONAR ($N \geq 1$) **3.** N-DOF ($N \geq 1$) **4.** 2N-DOF LEONAR

Insertion of foam (classical or advanced internal structure)



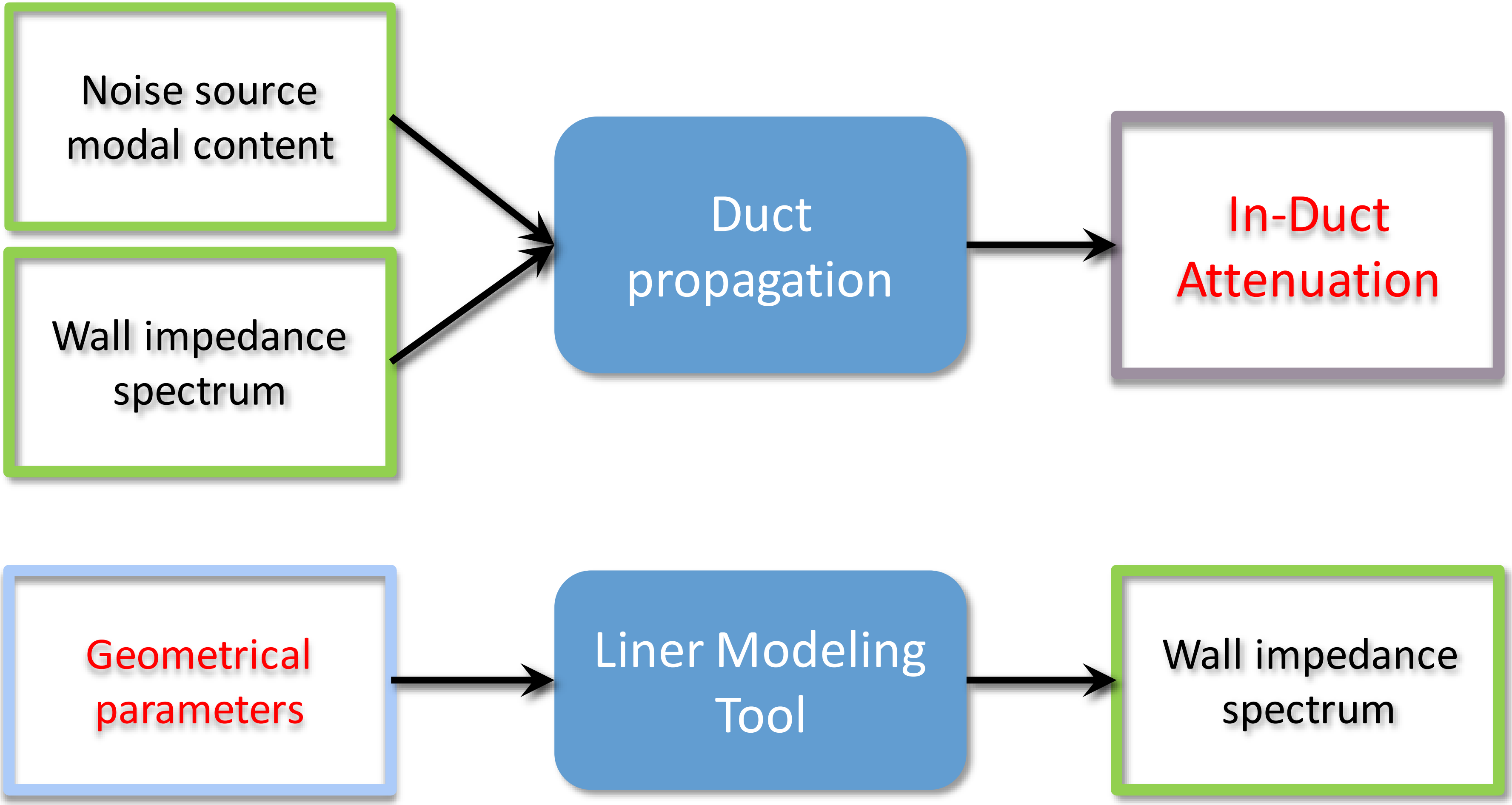


# Outline

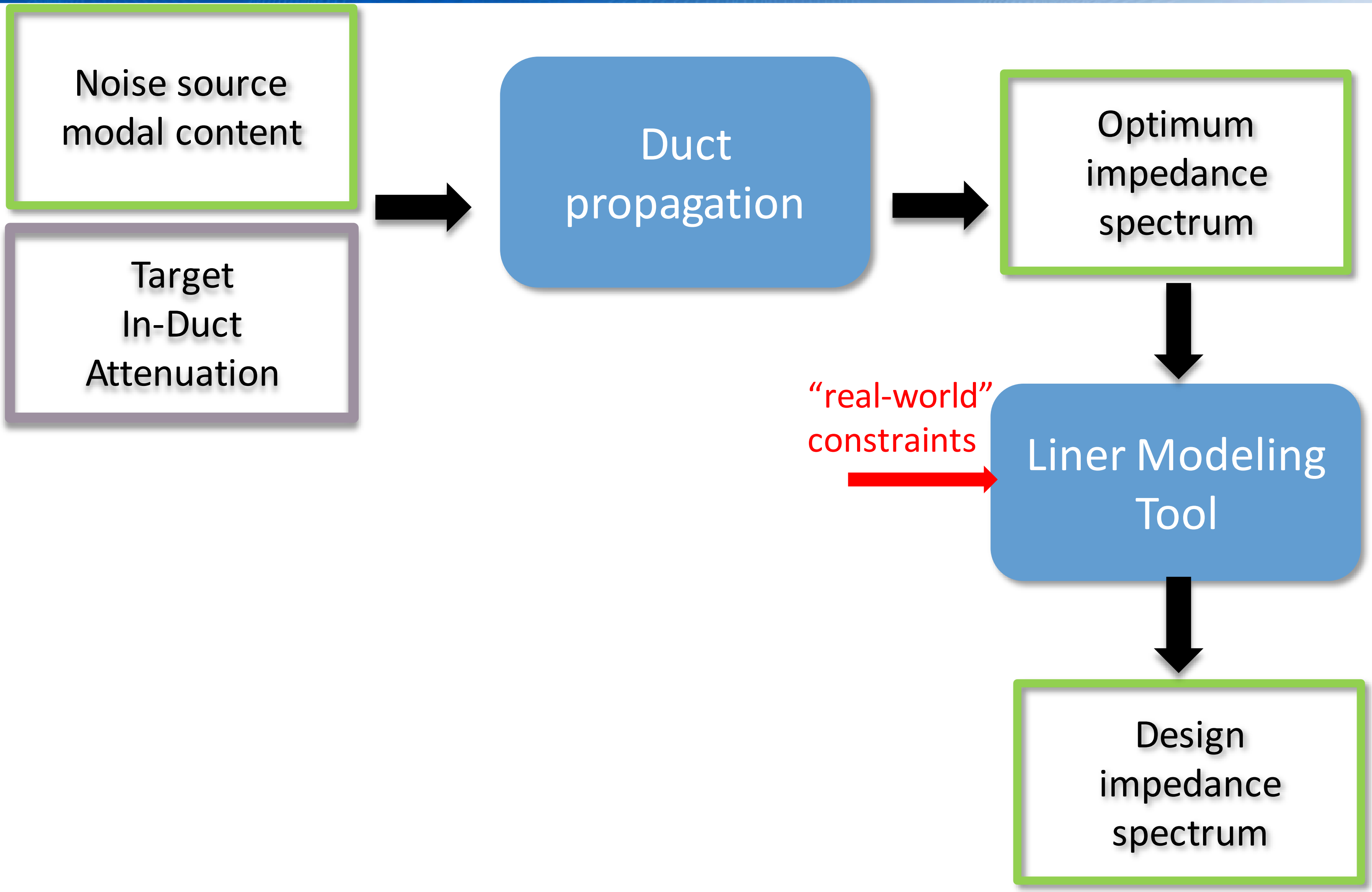
- Context
- **Liner design strategy**
- Uncertainty quantification
- Illustration on recent ONERA activities

# Liner design strategy




**Objective:** find the liner design which will yield the targeted in-duct attenuation

# Liner design loop



# Typical industrial requirements

RTCA DO-160G (FAA and EUROCAE).

« Environmental Conditions and test Procedures for Airborne Equipment »

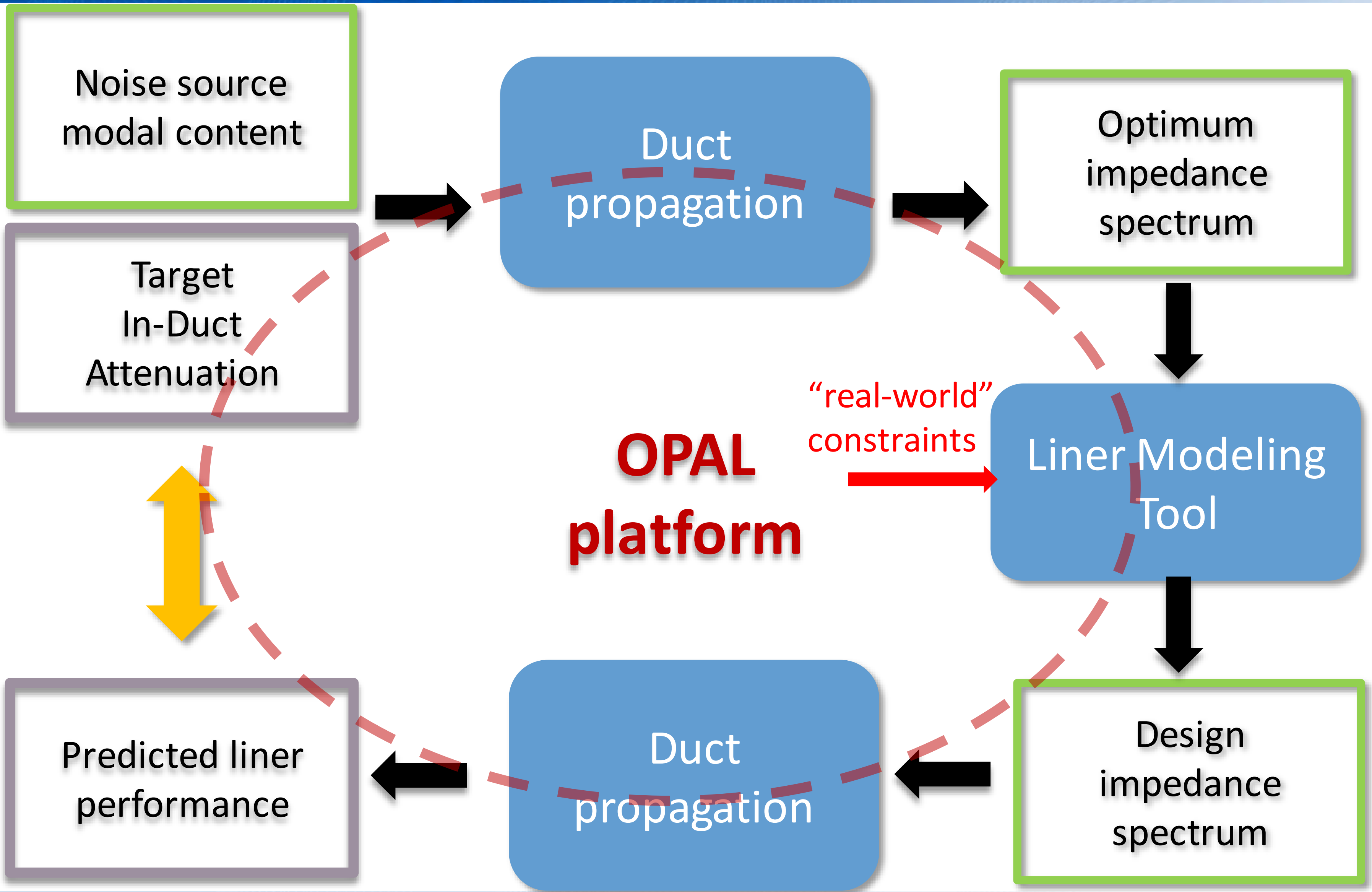
Section 4 : Temperature and Altitude
Section 5 : Temperature variation
Section 6 : Humidity
Section 8 : Vibration
Section 10 : Waterproofness
Section 11 : Fluid susceptibility
Section 12 : Sand and dust
Section 14 : Salt fog

**Example of requirements for engine noise mitigation:**

- Aerodynamic behaviour: negligible impact
- Weight: max 8kg/m²
- Temp.: max 600-650 ° C
- Mach: 0.5-0.6
- Fatigue strength, vibration, thermal cycle, thermal gradient, fire, drainage, 100000 – 200000 h
- Manufacturing costs

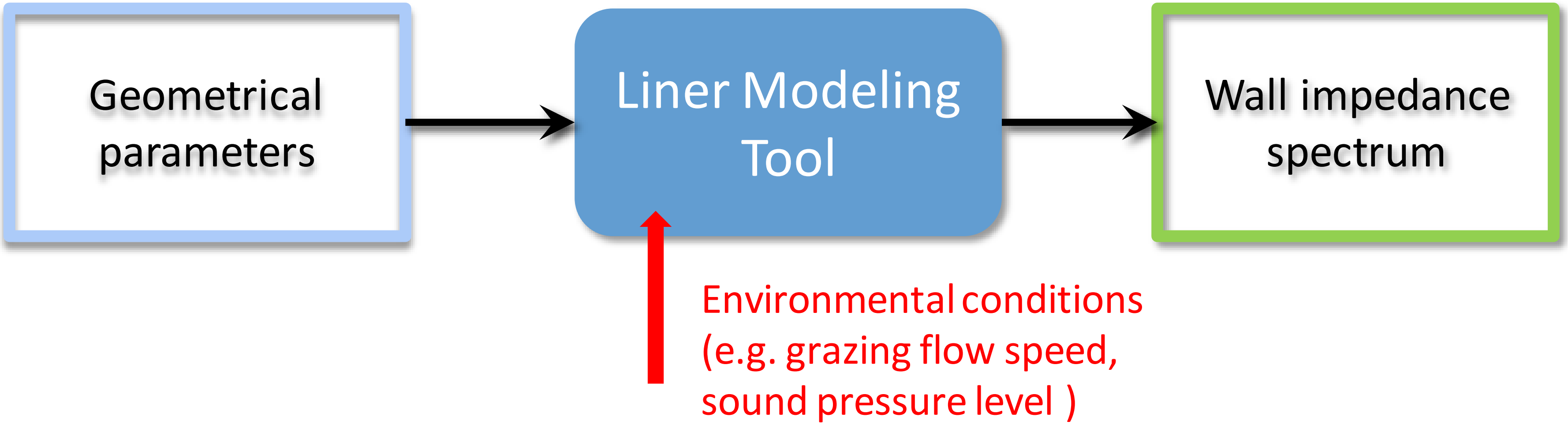
| Area | Air inlet | Cold duct downstream | Hot nozzle | Hot plug duct |
| --- | --- | --- | --- | --- |
| Max thickness (mm) | 50 | 20-30 | 15 | 200 |
| Optimum Impedance Spectrum | R/ρc: 2 to 3<br>X/ρc: -0.5 to -1 | R/ρc: 1 to 1.5<br>X/ρc: 0 to -0.6 | R/ρc: 1 to 2<br>X/ρc: 0 to -0.5 | R/ρc: 0.5 to 1.5<br>X/ρc: 0 to -0.3 |

# Liner design loop



# Liner design loop

Key element: **liner modeling tool**




Basis of most liner modeling tools: **semi-empirical models** fitted on experimental results.

Example for a perforated plate (Kirby & Cummings 1998, Malmary et. al 2001):

$$Z = \frac{\sqrt{2\nu\omega}}{\sigma c_0}\frac{h}{\delta} + \left[26{,}16\left(\frac{h}{2\delta}\right)^{-0{,}169} - 20\right]\frac{v^*}{\sigma c_0} - 0{,}645\frac{\omega h}{\sigma c_0} + \frac{4}{3\pi}\frac{1-\sigma^2}{\sigma c_0 {C_D}^2}|\boldsymbol{v}'.\boldsymbol{n}| + j\frac{\omega}{\sigma c_0}\left[h + \frac{16\delta}{3\pi}\right]$$

# Liner design loop

How are the semi-empirical impedance models derived?

➔ **impedance eduction**

- Direct impedance measurement (e.g. Kirby & Cummings 1998)

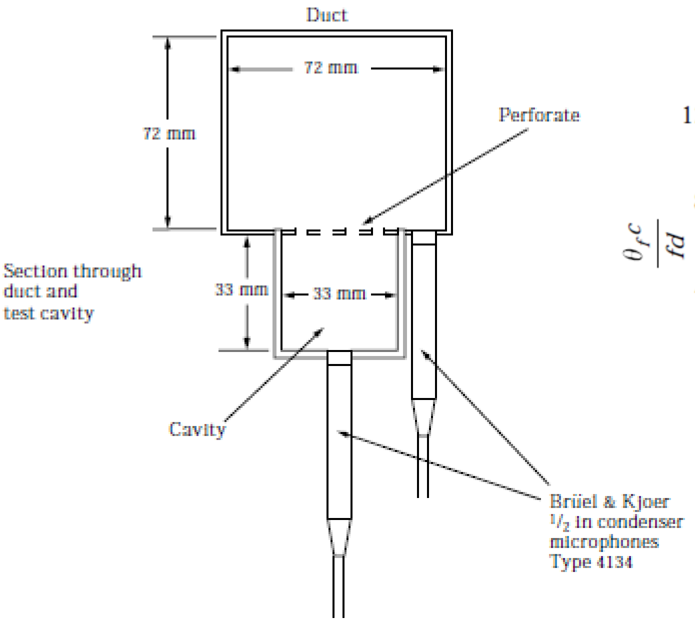
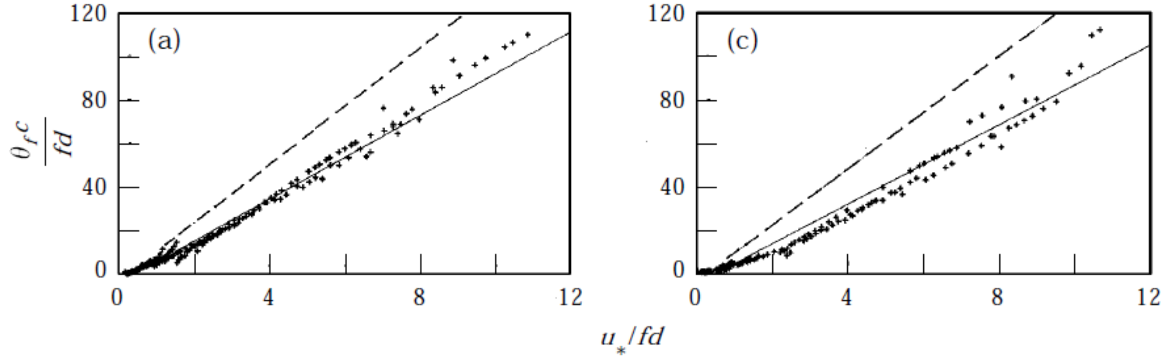



Figure 1. Apparatus for the measurement of the acoustic impedance of a perforate.

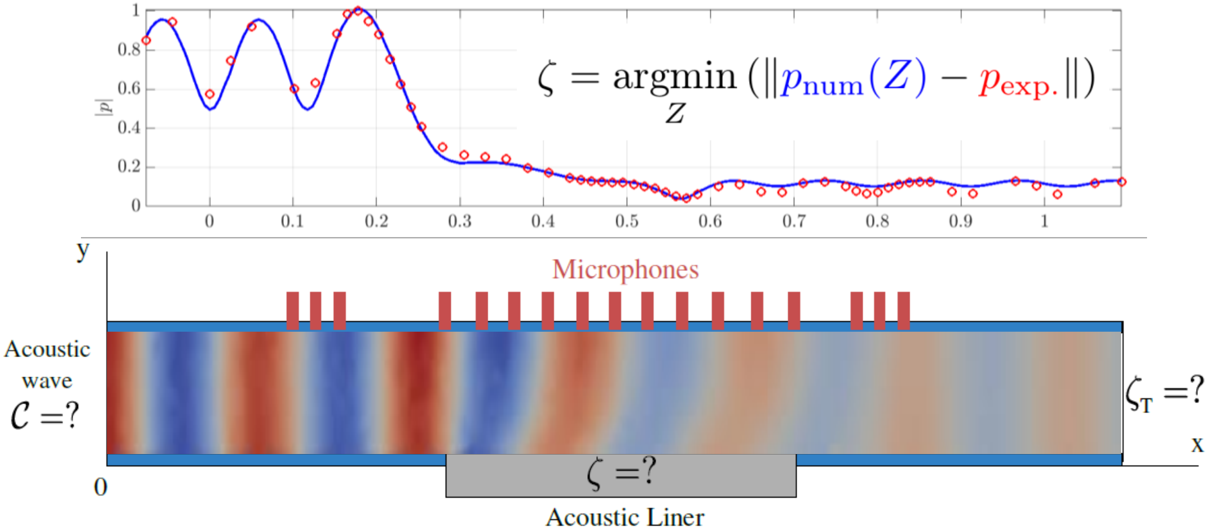


# Liner design loop

How are derived the semi-empirical impedance models?

➔ **impedance eduction**

- Direct impedance measurement (e.g. Kirby & Cummings 1998)
- Indirect methods (e.g. NASA, LAUM, DLR, ONERA, KTH…)



# Liner design loop

How are derived the semi-empirical impedance models?

➔ **impedance eduction**

- Direct impedance measurement (e.g. Kirby & Cummings 1998)
- Indirect methods (e.g. NASA, LAUM, DLR, ONERA, KTH…)

➔ fit on experimental data to derive a multi-parameter model

$$Z = \frac{\sqrt{2\nu\omega}}{\sigma c_0}\frac{h}{\delta} + \left[26{,}16\left(\frac{h}{2\delta}\right)^{-0{,}169} - 20\right]\frac{v^*}{\sigma c_0} - 0{,}645\frac{\omega h}{\sigma c_0} + \frac{4}{3\pi}\frac{1-\sigma^2}{\sigma c_0 {C_D}^2}|\boldsymbol{v}'.\boldsymbol{n}| + j\frac{\omega}{\sigma c_0}\left[h + \frac{16\delta}{3\pi}\right]$$

Two questions arise:

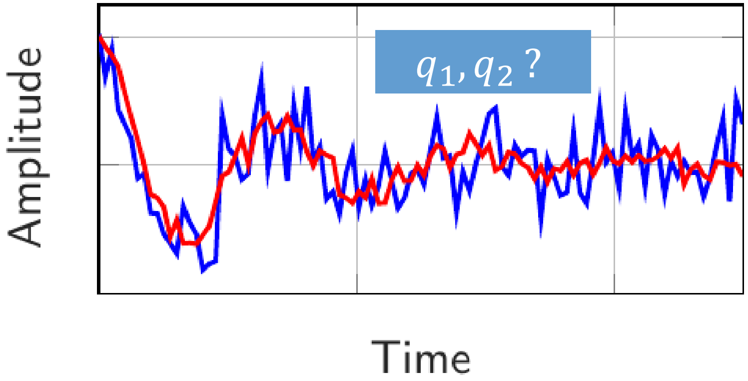
- what is the sensitivity of the impedance to the model formulation?
- what is the sensitivity of the impedance to an error in the model parameters?

**Key issue**: dealing with the **uncertainty**

# Outline

- Context
- Liner design strategy
- **Uncertainty quantification**
- Illustration on recent ONERA activities

# Statistical inference: Bayesian framework




**Modeling**

$$\ddot{y}(t) + q_1^2 \dot{y}(t) + q_2 y(t) = 0$$

$$y(0) = 2 \quad \dot{y}(0) = -q_1^2$$

**Deterministic** $\boldsymbol{q}_{\text{optim}} = \arg\min_{\boldsymbol{q}} \left( \|y - y_{\text{exp}}\|_2 + r(\boldsymbol{x}) \right)$

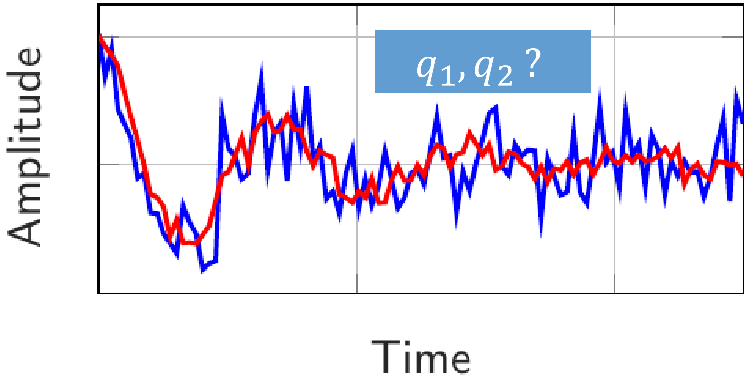
- Ill-posedness of inverse problems : non-uniqueness, instability
- No uncertainty quantification

**A posteriori** : given $y_{exp}$, what probability density for $(q_1, q_2)$ ?

$$\boldsymbol{\pi}(q|y_{exp}) = \frac{\overbrace{\boldsymbol{\pi}(y_{exp}|q)}^{\text{Likelihood}} \ \overbrace{\boldsymbol{\pi}(q)}^{\text{Prior}}}{\boldsymbol{\pi}(y_{exp})}$$

$$\boldsymbol{\pi}(y_{exp}|q) = \prod_j \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left( -\frac{|y_{exp}(t_j) - y(t_j)|^2}{2\sigma^2} \right)$$

# Statistical inference: Bayesian framework

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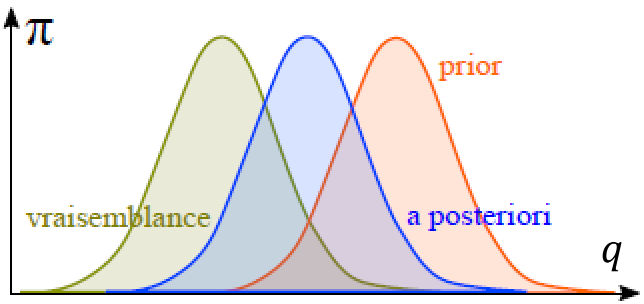




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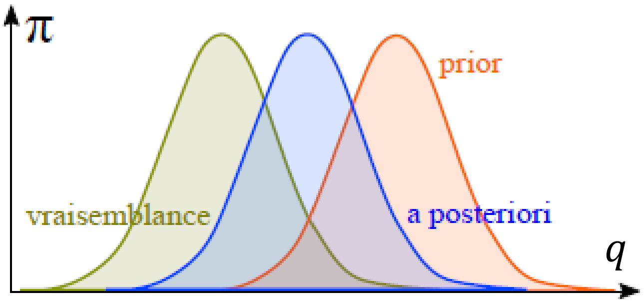
# Statistical inference: Bayesian framework

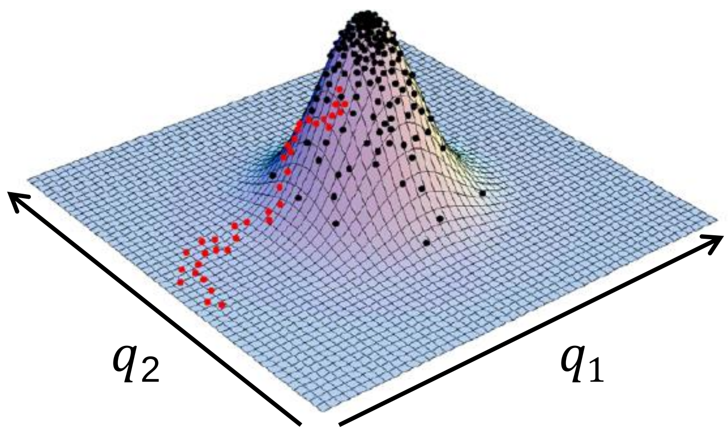
$$\boldsymbol{\pi}(q|y_{exp}) = \frac{\overbrace{\boldsymbol{\pi}(y_{exp}|q)}^{\text{Likelihood}}\ \overbrace{\boldsymbol{\pi}(q)}^{\text{Prior}}}{\boldsymbol{\pi}(y_{exp})}$$




How to sample from $\boldsymbol{\pi}(q|y_{exp})$ without knowing $\boldsymbol{\pi}(y_{exp})$ ?

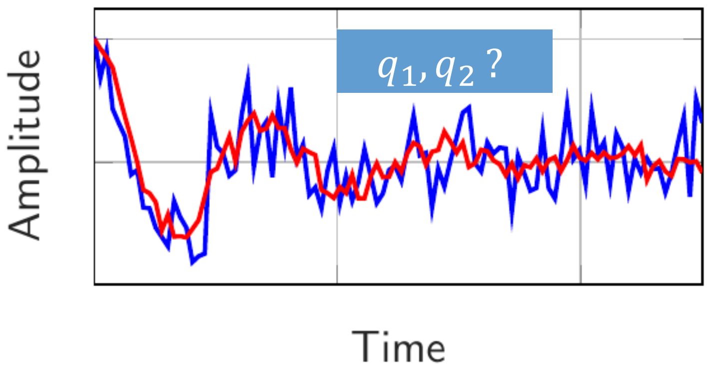
➔ **M**onte **C**arlo **M**arkov **C**hain strategy

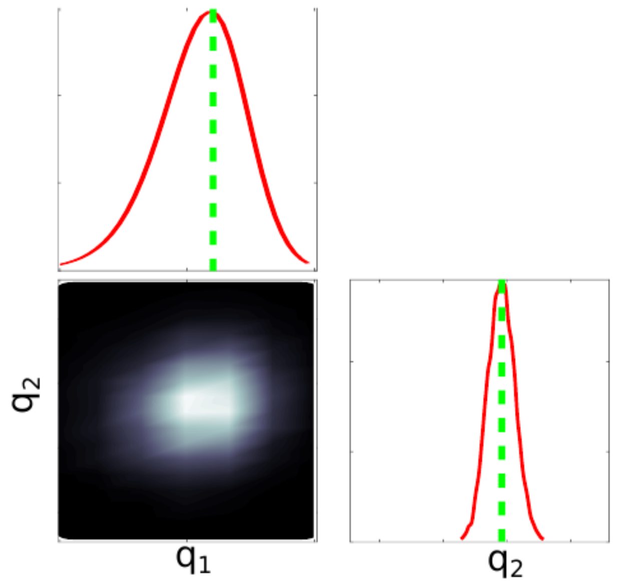
Random-walk generation of $y^{(k)}$ samples by exploring the space of $q$ ➔ creation of a Markov Chain whose stationary distribution is $\boldsymbol{\pi}(q|y_{exp})$



# Statistical inference: Bayesian framework

Illustration of results




with prior knowledge

# Statistical inference: Bayesian framework

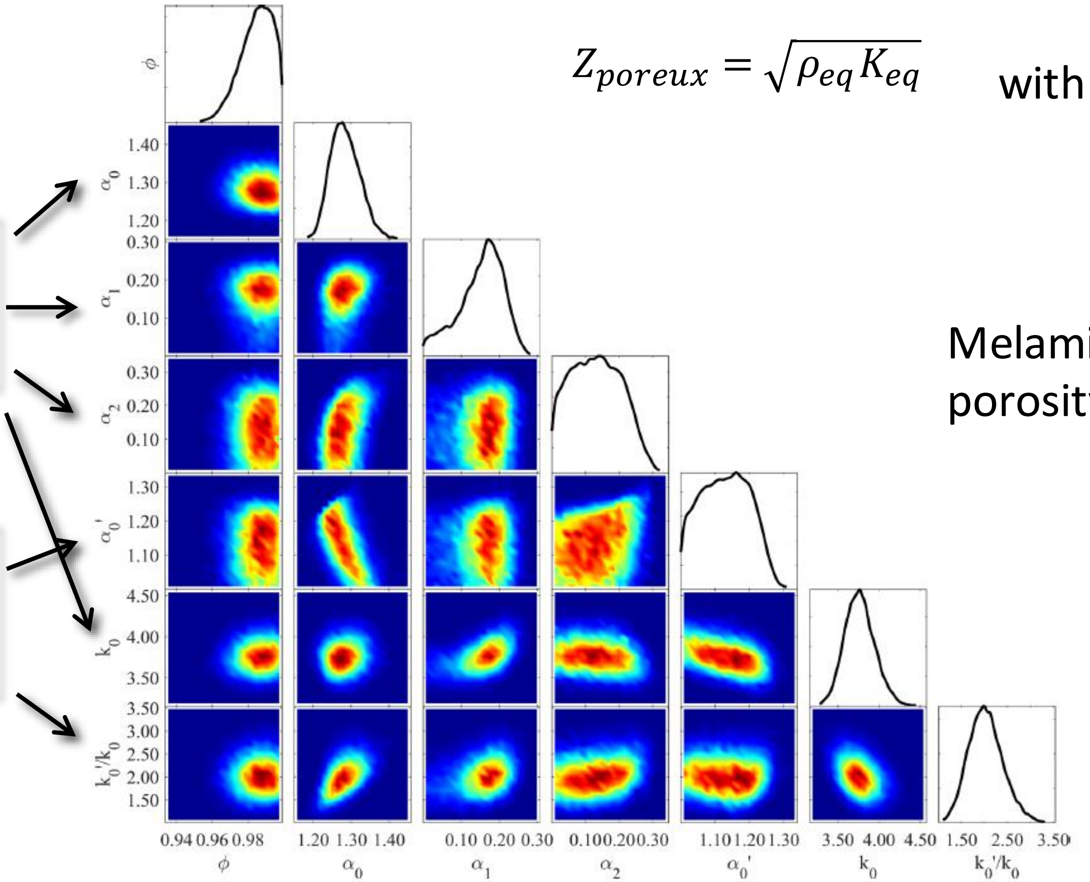
## Application to porous characterization

Roncen et al. JASA vol 144 (July&Dec.) 2018;
Roncen et al JASA vol 145 (March & Sep.) 2019

$$Z_{poreux} = \sqrt{\rho_{eq} K_{eq}} \quad \text{with} \quad \begin{aligned} \rho_{eq} &= \rho_f \, \alpha(\omega) \\ K_{eq} &= \rho_f c_f^2 / \beta(\omega) \end{aligned}$$

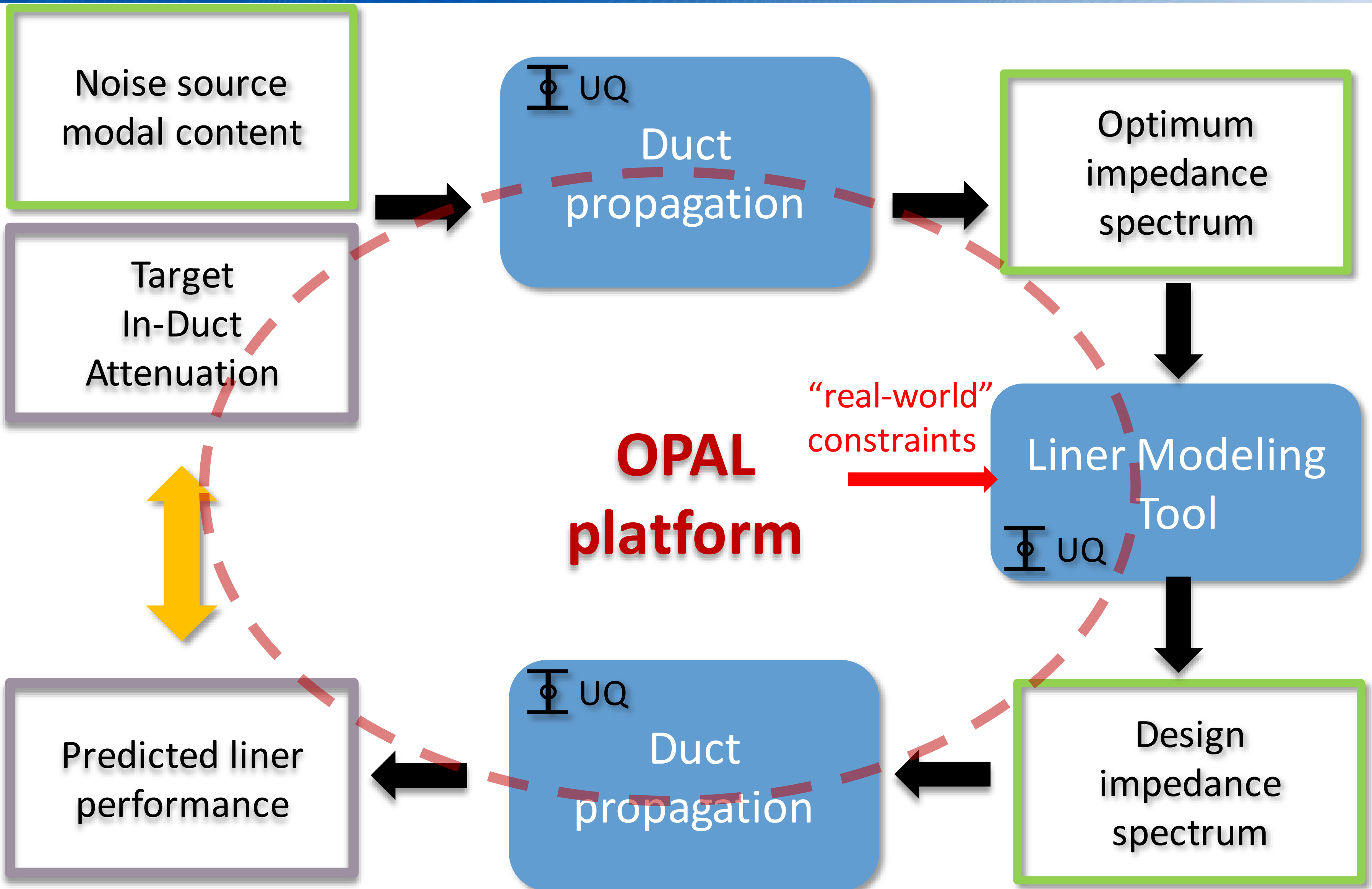
*Linked to the dynamic tortuosity*

*Linked to the dynamic compressibility*




Melamine-like foam of high porosity and low resistivity

# Liner design loop including UQ

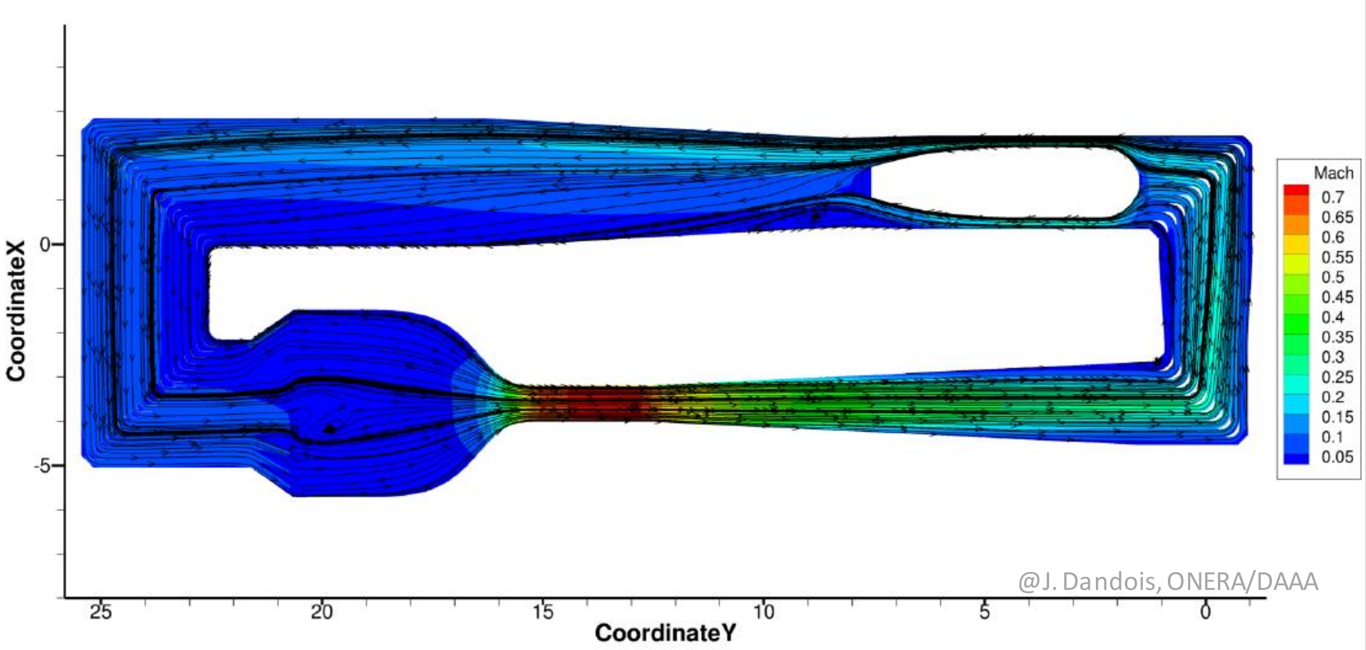


# Outline

- Context
- Liner design strategy
- Uncertainty quantification
- **Illustration on recent ONERA activities**

# Some recent applications at ONERA

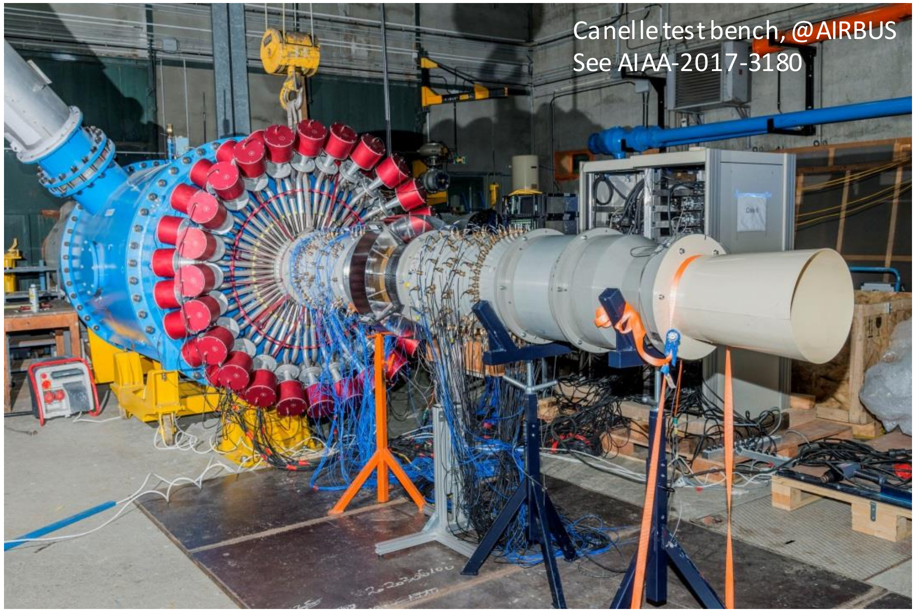
- **Acoustic treatment of wind tunnels**

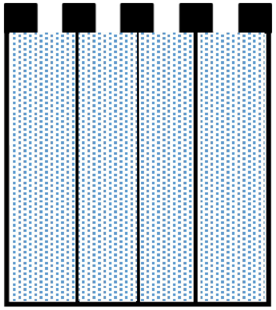



- Main challenges:
  - High-speed grazing flow (up to Mach 0,85)
  - Stringent compactness requirements
  - Mechanical resistance

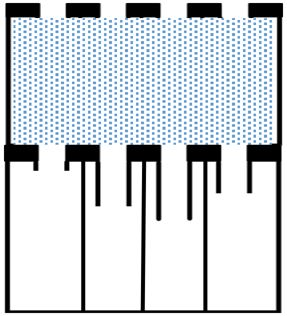
# Some recent applications at ONERA

- **Acoustic treatment of wind tunnels**



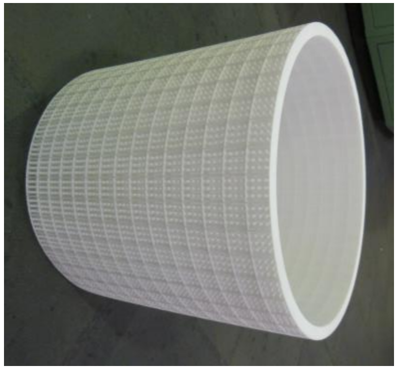



Perforate + foam



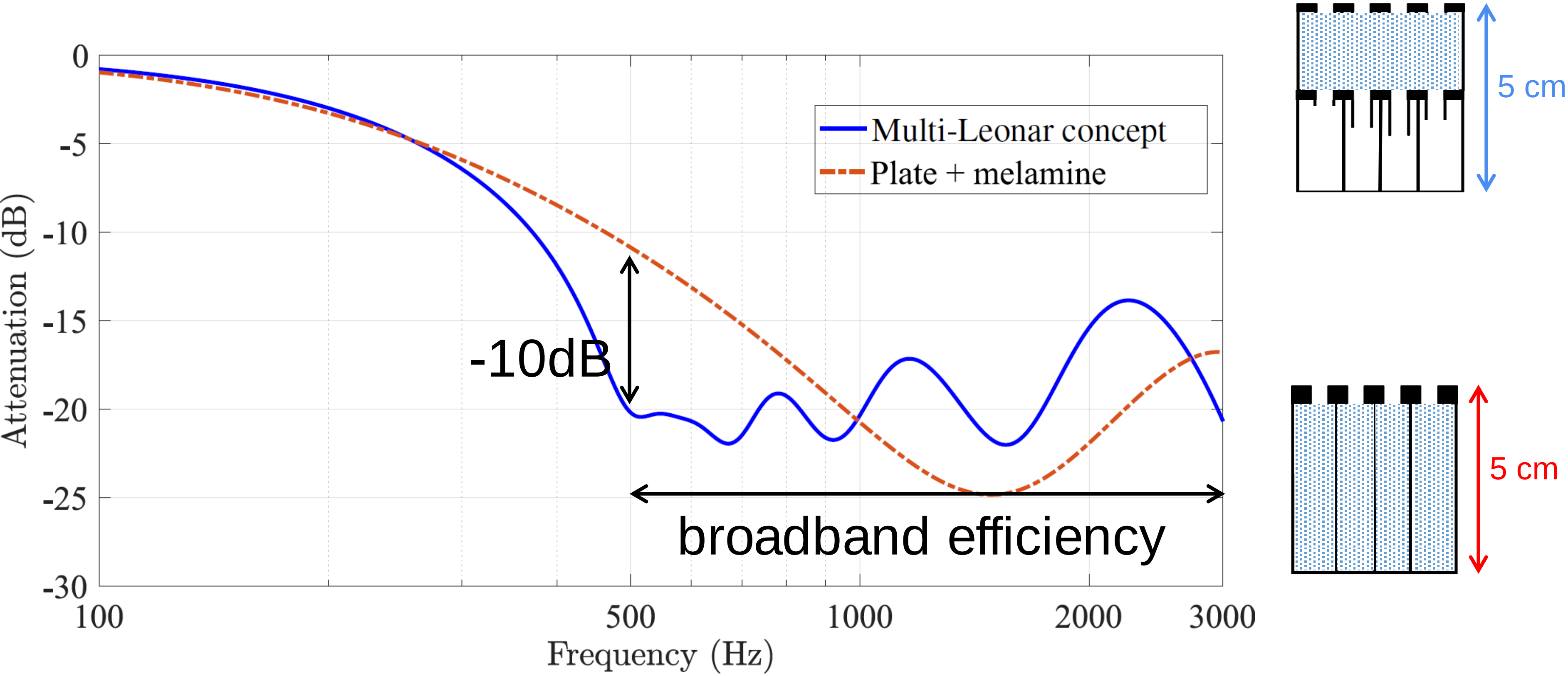
Multi-Leonar

- Design process
  - Numerical assessment of several concepts (OPAL tool) on the target configuration (WT)
  - Experimental check of the achieved impedance on a simplified configuration (Cannelle bench)
  - Manufacturing and installation in the WT



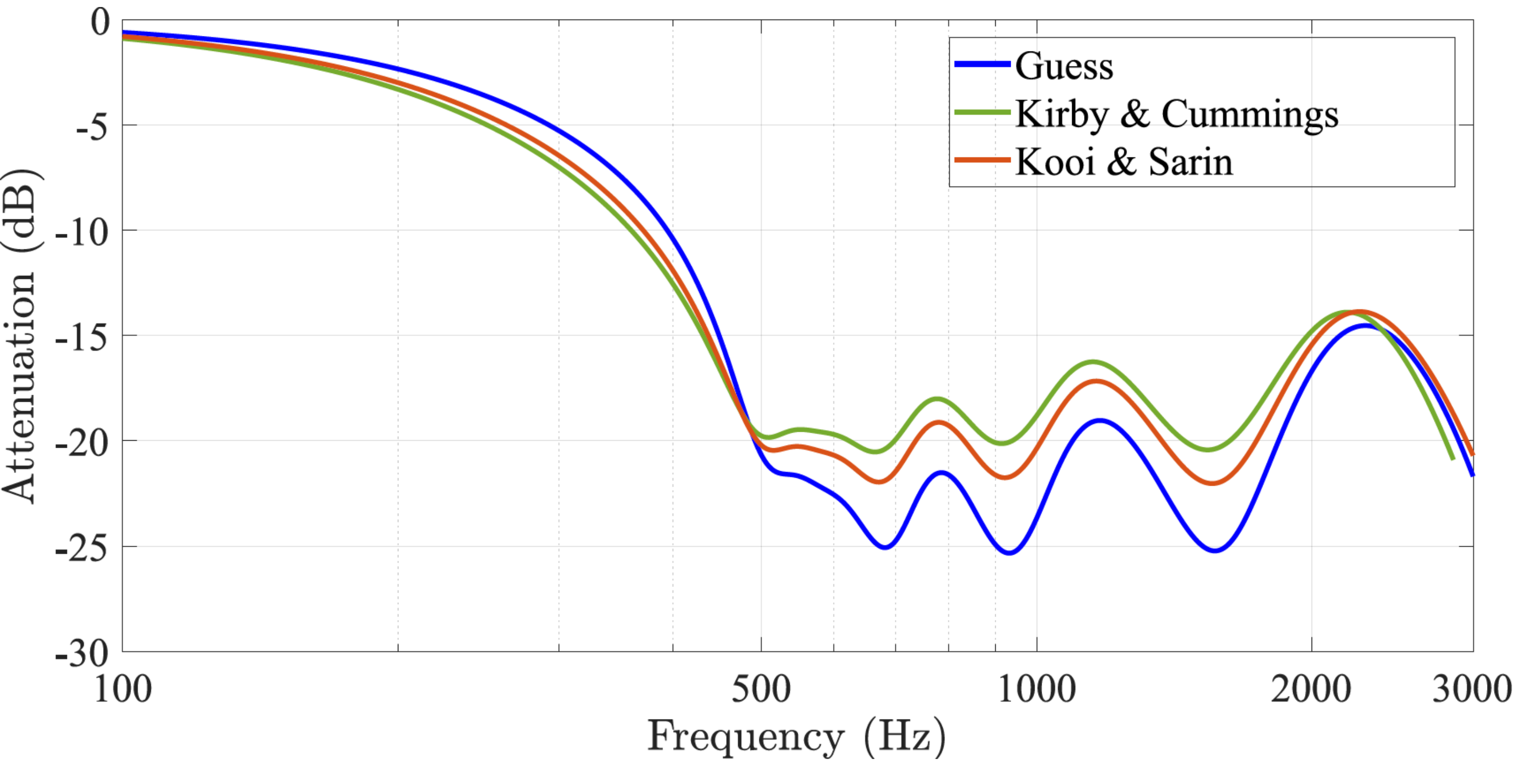
# Some recent applications at ONERA

- **Acoustic treatment of wind tunnels**



# Some recent applications at ONERA

- **Acoustic treatment of wind tunnels**



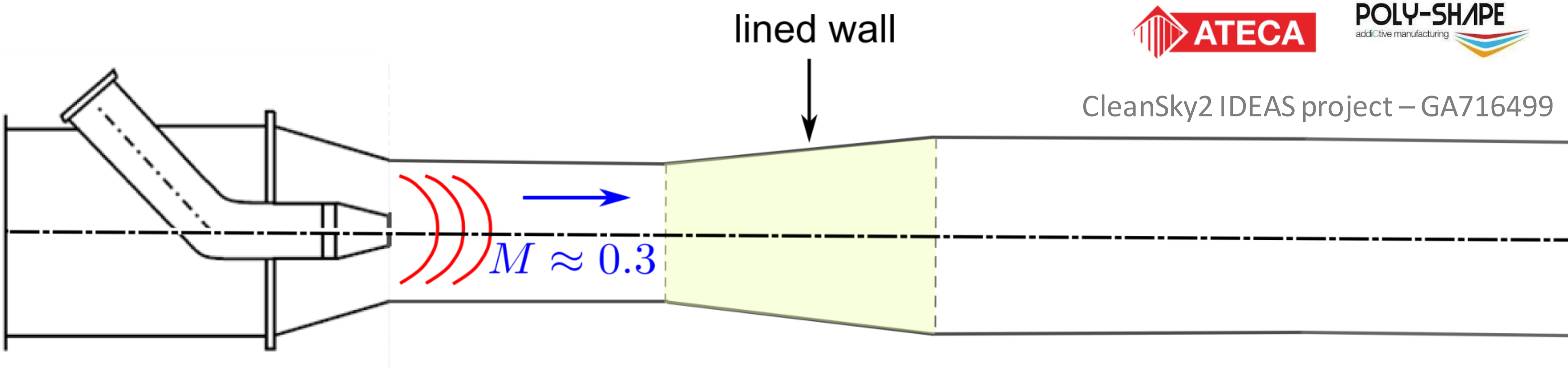

Low sensitivity of the solution to the grazing flow model (@M=0,9)

➔ To be checked experimentally

# Some recent applications at ONERA

- **Acoustic treatment of air conditioning systems**

CleanSky2 IDEAS project – GA716499

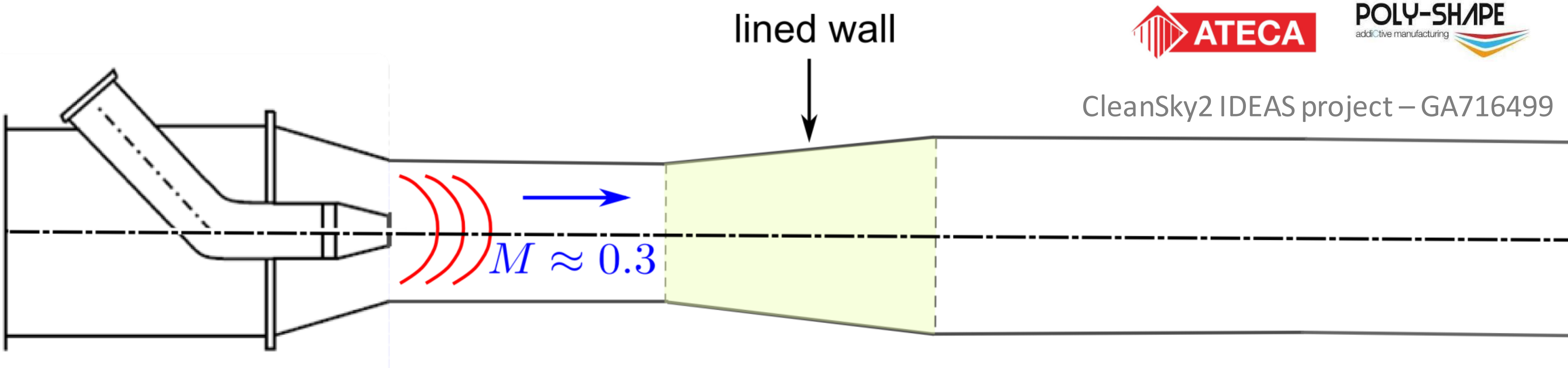



- Main challenges:
  - Stringent weight requirements
  - Temperature resistance
  - Manufacturing costs

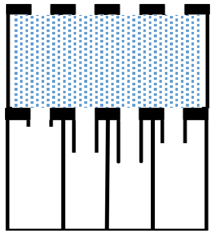
# Some recent applications at ONERA

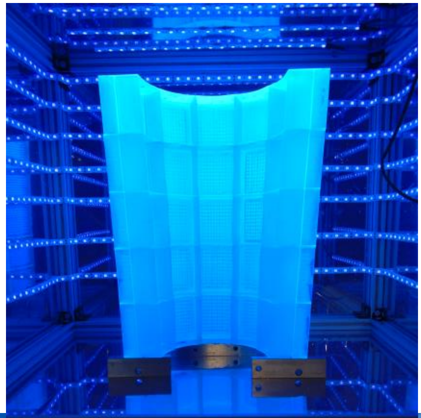
- **Acoustic treatment of air conditioning systems**

CleanSky2 IDEAS project – GA716499



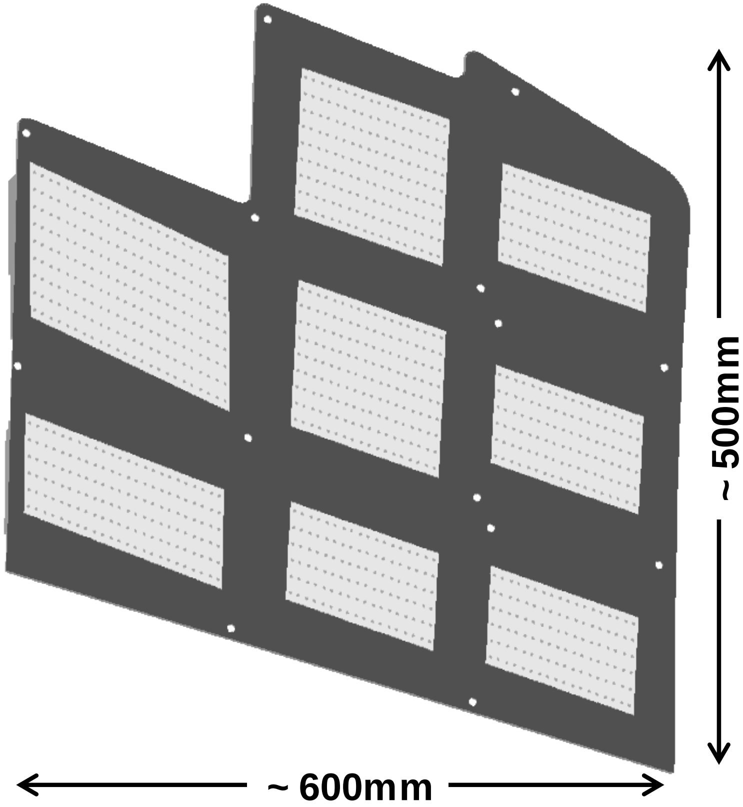

- Outcome of the design process:
  - DDOF liner with combination of foam and Leonar layers

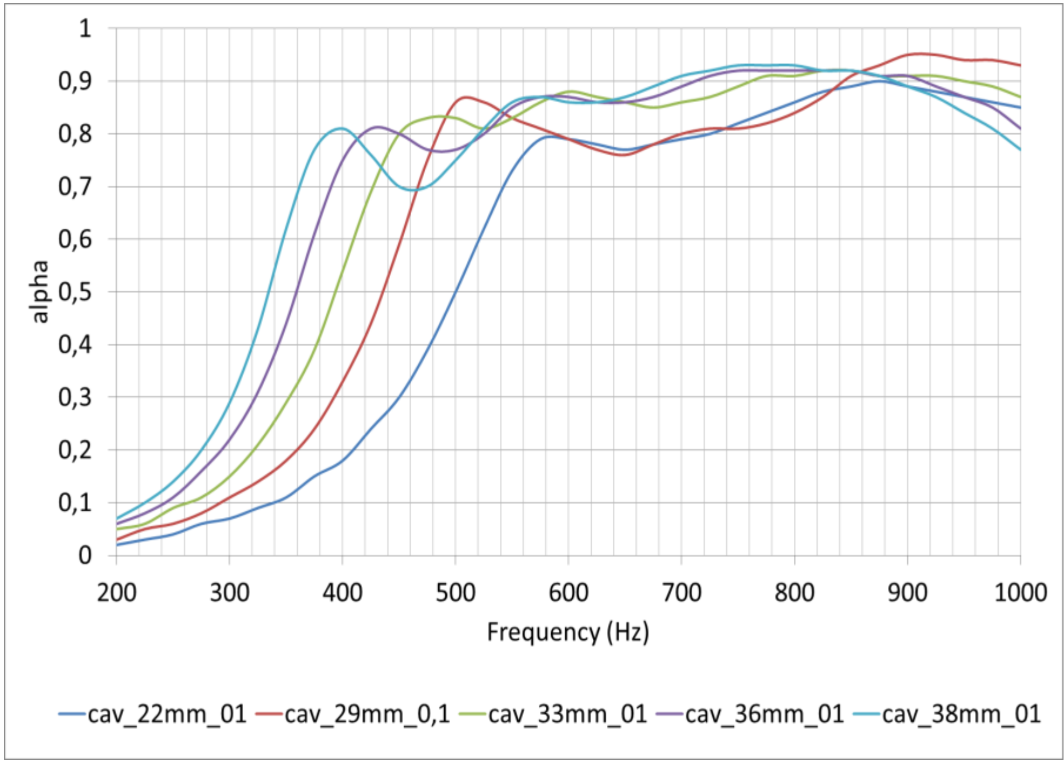




# Some recent applications at ONERA

- **Broadband absorption of airframe noise**



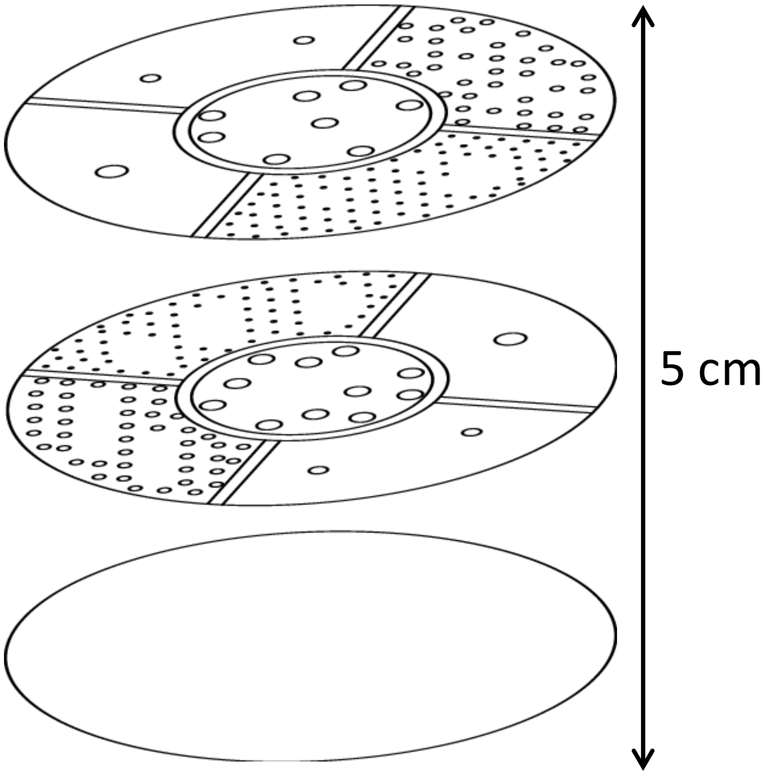




Combination of N-DOF LEONAR

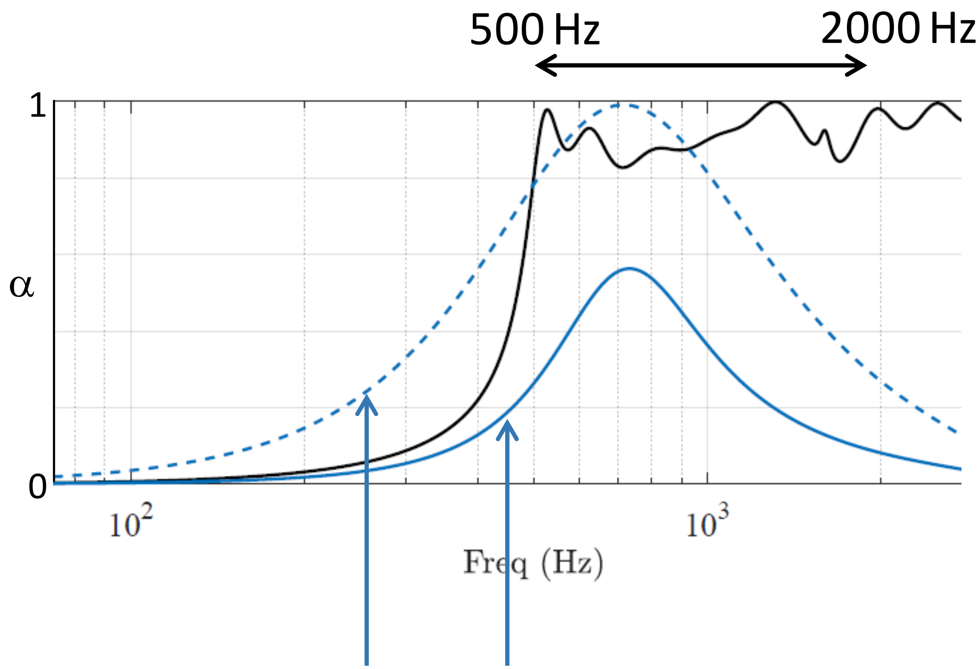
Broadband absorption at low-frequency, with a very compact solution (~3 cm)

# Some recent applications at ONERA

- **Low&broadband frequency liner (ONERA/TSAGI coop.)**




2-DOF liner with complex perforation layout




Perforate + honeycomb cavity at low (solid lines) and high (dashed lines) SPL

# Conclusions

- **Need in the aeronautics industry of new liner solutions for noise mitigation of the innovative flying concepts**
- **New material technologies, especially additive manufacturing, have broadly opened the design space for liner concepts**
- **Manufacturing and operational constraints must be taken into account all along the liner design process**
- **Uncertainty quantification must be addressed to ensure robustness of the design outcome → work in progress in the ONERA liner design platform (OPAL)**

# Thank you for your attention!