Advanced identification techniques and design tools applied to innovative aeroacoustic liners

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Outline

• Context
• Liner design strategy
• Uncertainty quantification
• Illustration on recent ONERA activities
Use of liners in nacelle of aircraft engines to reduce fan, turbine and combustion noise

Use of liners in wing leading edge to reduce interaction noise

Use of liners along a duct to reduce jet pump noise

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

- **Single Degree of Freedom liner (SDOF):**
  1 resistive layer (~porous) above 1 cavity (reactive)

- **Double Degree of Freedom liner (DDOF):**
  2 resistive layers and 2 cavities

**Absorption in a narrow frequency band**

**Locally reacting behavior**

Surface **impedance:**

\[ Z(\omega) = \frac{p'}{v'.n} \]

\[ Z(\omega) = R(\omega) + jX(\omega) \]
Context

Resistive layers

« (Micro) holes »

« parallel slits »

« wiremesh »

SDOF

2DOF

Micro-perf
Wiremesh

Honeycomb

Honeycomb cells
New challenges for noise mitigation with acoustic liners

UHBR engines

- Broadband, low frequency noise source
- Limited space available for liner installation

Urban air-taxi

Distributed Electrical Propulsion
Context

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

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)

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

1. Noise source modal content
2. Target In-Duct Attenuation
3. Duct propagation
4. Optimum impedance spectrum
5. Liner Modeling Tool
6. “real-world” constraints
7. Design impedance spectrum

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Typical industrial requirements

RTCA DO-160G (FAA and EUROCAE).
« Environmental Conditions and test Procedures for Airborne Equipment »

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

<table>
<thead>
<tr>
<th>Area</th>
<th>Air inlet</th>
<th>Cold duct downstream</th>
<th>Hot nozzle</th>
<th>Hot plug duct</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Max thickness (mm)</strong></td>
<td>50</td>
<td>20-30</td>
<td>15</td>
<td>200</td>
</tr>
<tr>
<td><strong>Optimum Impedance Spectrum</strong></td>
<td>( \frac{R}{\rho c} ): 2 to 3 ( \frac{X}{\rho c} ): -0.5 to -1</td>
<td>( \frac{R}{\rho c} ): 1 to 1.5 ( \frac{X}{\rho c} ): 0 to -0.6</td>
<td>( \frac{R}{\rho c} ): 1 to 2 ( \frac{X}{\rho c} ): 0 to -0.5</td>
<td>( \frac{R}{\rho c} ): 0.5 to 1.5 ( \frac{X}{\rho c} ): 0 to -0.3</td>
</tr>
</tbody>
</table>
Liner design loop

Key element: **liner modeling tool**

Geometrical parameters → [Liner Modeling Tool] → Wall impedance spectrum

Environmental conditions (e.g. grazing flow speed, sound pressure level)

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):

\[
Z = \frac{\sqrt{2\nu \omega h}}{\sigma c_0 \delta} + \left[ 26,16 \left( \frac{h}{2\delta} \right)^{-0.169} - 20 \right] \frac{v^*}{\sigma c_0} - 0,645 \frac{\omega h}{\sigma c_0} + \frac{4}{3\pi} \frac{1 - \sigma^2}{\sigma c_0 C_D^2} |v' \cdot n| + j \frac{\omega}{\sigma c_0} \left[ h + \frac{16\delta}{3\pi} \right]
\]
Liner design loop

How are the semi-empirical impedance models derived?

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

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

How are derived the semi-empirical impedance models?

implance 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**

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

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

\[ \ddot{y}(t) + q_1 \dot{y}(t) + q_2 y(t) = 0 \]
\[ y(0) = 2 \quad \dot{y}(0) = -q_1^2 \]

**Deterministic** \( q_{\text{optimal}} = \arg\min_q (\|y - y_{\text{exp}}\|_2 + r(x)) \)
- Ill-posedness of inverse problems: non-uniqueness, instability
- No uncertainty quantification

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

\[ \pi(q|y_{\text{exp}}) = \frac{\text{Likelihood} \cdot \text{Prior}}{\pi(y_{\text{exp}})} \]
\[ \pi(y_{\text{exp}}|q) = \prod_j \frac{1}{\sqrt{2\pi \sigma^2}} \exp \left( -\frac{|y_{\text{exp}}(t_j) - y(t_j)|^2}{2\sigma^2} \right) \]
Statistical inference: Bayesian framework

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\[
\pi(q|y_{exp}) = \frac{\text{Likelihood \: Prior}}{\pi(y_{exp})} = \frac{\pi(y_{exp}|q) \pi(q)}{\pi(y_{exp})}
\]
Statistical inference: Bayesian framework

\[
\pi(q | y_{exp}) = \frac{\text{Likelihood}}{\pi(y_{exp})} \frac{\text{Prior} \pi(q)}{\pi(y_{exp})}
\]

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

⇒ Monte Carlo Markov Chain strategy

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

with prior knowledge
Application to porous characterization
Roncen et al. JASA vol 144 (July & Dec.) 2018; Roncen et al JASA vol 145 (March & Sep.) 2019

\[ Z_{\text{poreux}} = \sqrt{\rho_{eq} K_{eq}} \]

with

\[ \rho_{eq} = \rho_f \alpha(\omega) \]
\[ K_{eq} = \rho_f \frac{c_f^2}{\beta(\omega)} \]

Melamine-like foam of high porosity and low resistivity

Linked to the dynamic tortuosity
Linked to the dynamic compressibility
Liner design loop including UQ

Noise source modal content

Target In-Duct Attenuation

Predicted liner performance

Duct propagation

UQ

Optimum impedance spectrum

Design impedance spectrum

Liner Modeling Tool

"real-world" constraints

OPAL platform
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**

- **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

![Graph showing broadband efficiency and attenuation](image)

-10dB
Some recent applications at ONERA

- Acoustic treatment of wind tunnels

![Graph showing attenuation vs. frequency]

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

  - Main challenges:
    - Stringent weight requirements
    - Temperature resistance
    - Manufacturing costs
Some recent applications at ONERA

- Acoustic treatment of air conditioning systems

- 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!