Design of Electroacoustic Absorbers using PID control

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Outline

• Context

• Electroacoustic absorbers

• Design on COMSOL Multiphysics

• Results and validation

• Conclusions and perspectives
CONTEXT
Context

- Objective: improve sound absorption in the low-frequency range

- Solution: impedance-based control of loudspeaker such as "electroacoustic absorbers"

- Low-frequency rooms equalization (audio)
- Damping of acoustic resonances (noise annoyance)
- Lowering of reverberation (room acoustics)

Applications
- residential soundproofing
- industrial machine noise control
Context

- **Feedback-based techniques**
  - Direct (proportional) feedback on acoustic quantities
    - H.F. Olson, electronic sound absorber, 1953
    - E. De Boer, theory of motional feedback, 1961

- **Shunt-based techniques**
  - Passive or active shunt network
  - Sensorless control
    - R.J. Bobber, active transducer as characteristic impedance, 1970

Lissek *et al.*, "Electroacoustic absorbers, bridging the gap between shunt loudspeakers and active sound absorption", JASA 129(5), 2011
Example

Damping of rooms’ modal behavior

Experimental setup
Reverberant chamber at EPFL-LEMA (volume 215.6 m³, tot. surface 226.9 m²)

Source ➔ shunt loudspeaker array at a corner
Excitation signal ➔ discrete swept sine with 0.1 Hz frequency steps from 30 Hz to 40 Hz, each step lasting 30s
Absorbers ➔ array of 10 shunt loudspeakers, each in 50 dm³ closed-box
Measurement ➔ SPL at corner #4 with B&K type 4165 electret microphone (50 mV/Pa)
ELECTROACOUSTIC ABSORBERS
Electroacoustic absorbers

1. Principle in 1D configuration

\[ Z_{\text{load}} = Z_{\text{line}} \rightarrow \text{Total absorption} \]

Load: electroacoustic absorber

Line: impédance tube

Source

\[ Z_{\text{line}} \quad \Box \quad Z_{c} \quad \Box \quad \Box \]

\[ Z_{\text{load}} \quad \Box \quad \frac{P_{m}(t)}{\nu_{m}(t)} \]

\[ z_{\text{norm}} \quad \Box \quad \frac{P_{m}(t)}{\Box \nu_{m}(t)} \]

Lissek et al., "Electroacoustic absorbers, bridging the gap between shunt loudspeakers and active sound absorption", JASA 129(5), 2011
Electroacoustic absorbers

2. Loudspeaker dynamics

- Mesh law and 2\textsuperscript{nd} Newton’s law

\[ B l i(t) s S_d P_m(t) t R_{ms} v_m(t) \frac{dv_m(t)}{dt} \frac{1}{C_{ms}} v_m(t) dt \]

\[ u(t) = R_e i(t) L_e \frac{di(t)}{dt} + B l v_m(t) \]

- \( B l \) (N.A\textsuperscript{-1}): force factor
- \((R_{ms}, m_s, C_{ms})\): speaker mechanical parameters
- \((R_e, L_e)\): driver electrical parameters
- \( S_d (m^2)\): equivalent diaphragm area

Lissek et al., "Electroacoustic absorbers, bridging the gap between shunt loudspeakers and active sound absorption", JASA 129(5), 2011
Electroacoustic absorbers

2. Loudspeaker dynamics

• Mesh law and 2\textsuperscript{nd} Newton’s law

\[
Bli_s s S_d P_m s Z_m v_m(s) \\
U s Z_e i s B l v_m(s)
\]

\[s \equiv j\square\]

- \(Bl\) (N.A\textsuperscript{-1}): force factor
- \(Z_m\) (N.s.m\textsuperscript{-1}): mechanical impedance
- \(Z_e\) (Ω): electrical impedance
- \(S_d\) (m\textsuperscript{2}): equivalent diaphragm area

Loudspeaker can be turned into an absorber of sound ("Electroacoustic absorber")

Lissek et al., "Electroacoustic absorbers, bridging the gap between shunt loudspeakers and active sound absorption", JASA 129(5), 2011
Electroacoustic absorbers

3. Impedance control

Impedance matching

\[ z_{\text{norm}} = \frac{p_m}{c v_m} = 1 \]

Command law

\[ e(t) \square \frac{P_m(t)}{c} - v_m(t) \]

Goal: minimize \( e(t) \)
yields \( z_{\text{norm}} \) tends to 1

\( p_m(t) \) and \( v_m(t) \) measurable
but only \( v_m(t) \) is controllable

• Control \( z_{\text{norm}} \) by feedback
Electroacoustic absorbers

4. PID control

- 2\textsuperscript{nd} order system
- Feeds back the loudspeaker with command voltage \( u(t) \) after error signal \( e(t) \)

\[
\frac{1}{\rho} e(t) \quad \leadsto \quad \text{PID} \quad \Rightarrow \quad \text{Haut-Parleur}
\]

\[
u(t) = K_p e(t) + K_i \int e(t) dt + K_d \frac{de(t)}{dt}
\]

Pressure \( p_m \) is considered as the reference but it is also the disturbance.
COMSOL MODEL
COMSOL Model

1. General setup

• FEM with Comsol Multiphysics®
  • Acoustic module
  • Structural mechanics
  • PID control

• 2D-axisymmetric model
  • Loudspeaker + box (COMSOL Tutorial)
  • Impedance tube
  • PID control

• PID ➔ Time-domain study
  • More complex than in the frequentual domain
COMSOL Model

2. Electroacoustic absorber

Baseline: COMSOL Tutorial ("Loudspeaker driver")

COMSOL Tutorial example + fine tuning (wrt exp. results)

Mechanical parameters modified to fit VISATON® AI170

- mass density
- Poisson modulus
- Young modulus

(see Moreau et al. Comsol Conference 2009)

<table>
<thead>
<tr>
<th>Component</th>
<th>$E$ (Pa)</th>
<th>$\nu$</th>
<th>$\rho$ (kg m$^{-3}$)</th>
<th>$m$ (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>dust cap</td>
<td>7e10</td>
<td>0.33</td>
<td>2700</td>
<td>1.1</td>
</tr>
<tr>
<td>diaphragm</td>
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<td>0.33</td>
<td>140</td>
<td>0.8</td>
</tr>
<tr>
<td>spider</td>
<td>1e7</td>
<td>0.45</td>
<td>215</td>
<td>0.9</td>
</tr>
<tr>
<td>outer suspension</td>
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<td>0.45</td>
<td>405</td>
<td>1.2</td>
</tr>
<tr>
<td>coil support</td>
<td>3.8e9</td>
<td>0.37</td>
<td>1500</td>
<td>0.6</td>
</tr>
<tr>
<td>voice coil</td>
<td>1.1e11</td>
<td>0.30</td>
<td>8700</td>
<td>7.5</td>
</tr>
</tbody>
</table>
COMSOL Model

2. Electroacoustic absorber

Baseline: COMSOL Tutorial ("Loudspeaker driver")

Feedback voltage:

\[ u \frac{d}{dt} K_p e(t) - K_i \int e(t) dt - K_d \frac{de(t)}{dt} \]

Assuming constant Bl

\[(p_m, v_m) \text{ probes } \Rightarrow e(t)\]
COMSOL Model

3. Waveguide

- Max mesh size < \( \lambda/5 \)
- One simulation for each frequency
- Electroacoustic absorber acoustic impedance processed on several periods

Output:

\[
Z_{\text{norm}} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} \left( \frac{P_{mi}}{N} \right)^2} - \sqrt{\frac{1}{N} \sum_{i=1}^{N} \left( \frac{V_{mi}}{N} \right)^2}
\]
VALIDATION
Validation

1. Proportional corrector

$z_{\text{norm}}$ vs frequency

Increasing $K_p$

<table>
<thead>
<tr>
<th>$Z_{\text{norm}}$</th>
<th>$f(\text{Hz})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>1000</td>
<td>1000</td>
</tr>
</tbody>
</table>

sans contrôle

$K_p=0.00175$

$K_p=0.0035$

$K_p=0.0105$

Increasing $K_p$

Increasing $K_p$

Increasing $K_p$
Validation

2. Proportional-Integral corrector

$|Z_{norm}|$ vs frequency

increasing $K_i$

$$k_p=0.0035 \quad k_i=2.5$$
$$k_p=0.0035 \quad k_i=5$$
$$K_p=0.0035 \quad k_i=0$$
Validation

3. Proportional-integral corrector

$z_{\text{norm}}$ vs frequency

<table>
<thead>
<tr>
<th>$Z_{\text{norm}}$</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
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</thead>
<tbody>
<tr>
<td>$f(\text{Hz})$</td>
<td>10</td>
<td>100</td>
<td>1000</td>
<td></td>
<td></td>
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<td></td>
<td></td>
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</tr>
</tbody>
</table>

increasing $K_d$

- $K_d=0, K_p=0.0035$
- $K_d=1\times10^{-6}, K_p=0.0035$
- $K_d=1\times10^{-5}, K_p=0.0035$
- $K_d=5\times10^{-6}, K_p=0.0035$

COMSOL Conference 2011 - Stuttgart
Lissek et al.- Electroacoustic absorbers
Validation

4. PID corrector

$Z_{\text{norm}}$ vs frequency
Validation

5. Validation vs. experiment
Without contrôle

With PID control
Reflecting setting

With PID control
Absorbant setting
CONCLUSIONS AND PERSPECTIVES
Conclusions

• Implementation of PID control for electroacoustic absorbers in COMSOL feasible
  ✓ Temporal approach
    OK, but time consuming
  ✓ Frequentiel approach
    similar results, but no insight of potential instabilities

• Better sound absorption capability through PID control
  ✓ Integral action has an effect below the resonance frequency
  ✓ Derivative action has an effect above
  ✓ I and D actions contribute to pole placement (frequentiel approach)
Perspectives

• This preliminary work gives the frame for further optimization study on the concept
  ✓ Especially for MEMs based electroacoustic absorbers (down-scaling of transducers)
• Possibility to implement electroacoustic absorbers in 3D configurations in COMSOL
  ✓ room acoustic equalization
  ✓ soundproofing solutions for industrial noise (especially as acoustic liners for aircraft engines)
  ✓ etc.
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THANK YOU FOR YOUR ATTENTION