

ROOM EQUALIZATION WITH ELECTROACOUSTIC ABSORBERS

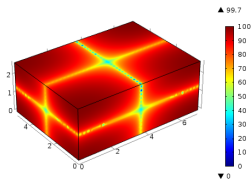
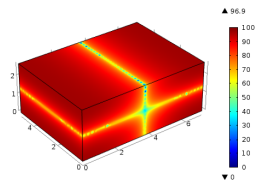
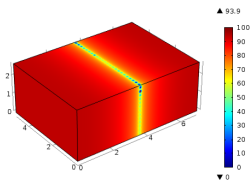
Hervé Lissek & Etienne Rivet

Signal Processing Laboratory 2 (LTS2)
École polytechnique fédérale de Lausanne, Switzerland

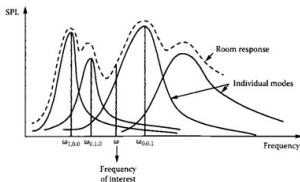
December 11, 2019



Listening Rooms at Low Frequencies

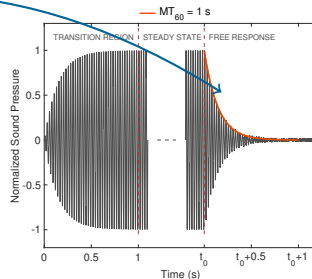
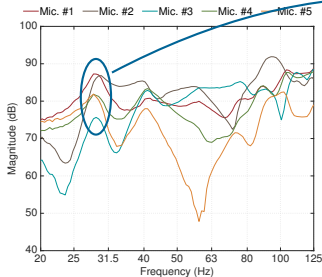


Listening Rooms at Low Frequencies



Modal decay time of mode n

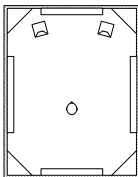
$$MT_{60n} = \frac{3 \ln(10) Q_n}{\pi f_{0n}}$$



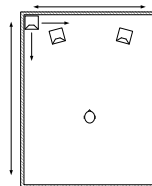
→ How to improve the listening experience in any room at low frequencies?

Correction Strategies

- Passive means



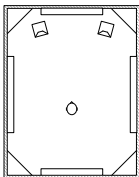
Passive absorbers



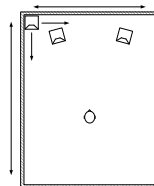
Optimal room design / configuration

Correction Strategies

- Passive means

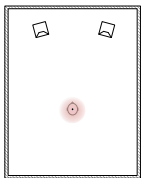


Passive absorbers

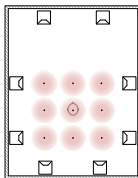


Optimal room design / configuration

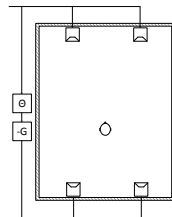
- Active equalisation



Single input



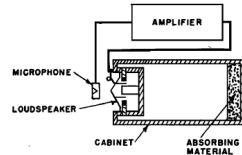
Multiple inputs



Plane wave propagation

Correction Strategies

- Active absorption

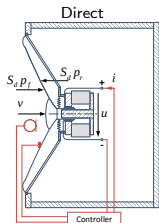


Olson and May, *J. Acoust. Am.*, 1953.

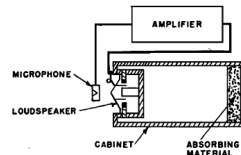
Correction Strategies

- Active absorption

→ Electroacoustic absorbers



Nicholson, *PhD thesis*, 1994

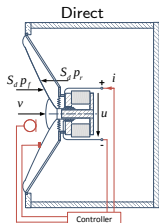


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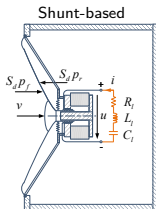
Correction Strategies

- Active absorption

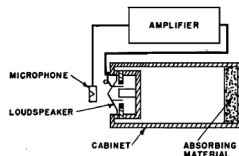
→ Electroacoustic absorbers



Nicholson, *PhD thesis*, 1994



Boulandet, *PhD thesis*, 2012

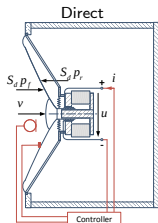


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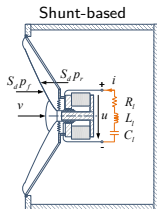
Correction Strategies

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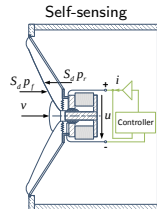
→ Electroacoustic absorbers



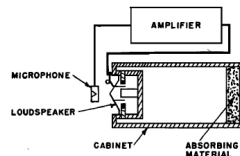
Nicholson, *PhD thesis*, 1994



Boulandet, *PhD thesis*, 2012



Boulandet et al., *Acta Acustica united with Acustica*, 2016

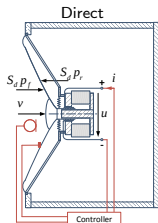


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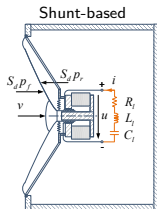
Correction Strategies

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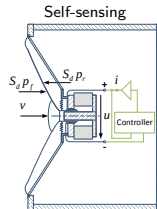
→ Electroacoustic absorbers



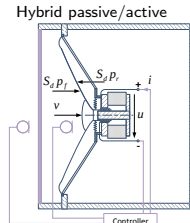
Nicholson, *PhD thesis*, 1994



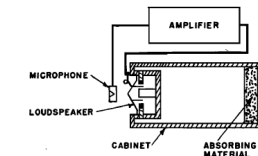
Boulandet, *PhD thesis*, 2012



Boulandet et al., *Acta Acustica united with Acustica*, 2016

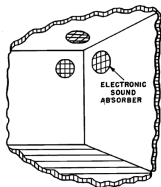


Galland et al., *Applied Acoustics*, 2005



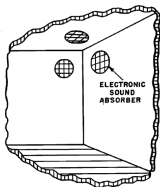
Olson and May, *J. Acoust. Am.*, 1953.

Motivation



- Preliminary experiment with sensorless electroacoustic absorbers in a lightly damped room
R. Boulandet, Tunable electroacoustic resonators through active impedance control of loudspeakers, *PhD thesis*, Ecole polytechnique fédérale de Lausanne (EPFL), 2012.

Motivation



- Preliminary experiment with sensorless electroacoustic absorbers in a lightly damped room

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- *INTERACTS* project



Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

h e p i a

Haute école du paysage, d'ingénierie
et d'architecture de Genève

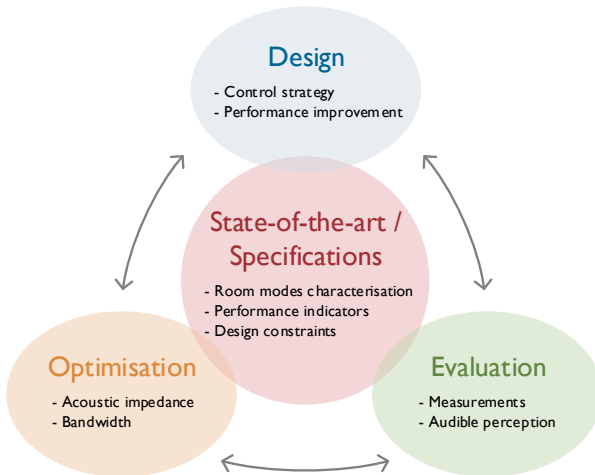


GOLDMUND
SWISS MADE



- Active absorption through impedance control
- "Plug-and-play" device
- Efficient whatever the geometry and damping of the room
- Stable and not vulnerable to changes (room occupancy)
- No audible sound from the device





1

Control Design

- Electroacoustic absorbers
- Modal Equalisation in 1D Case

2

Optimisation

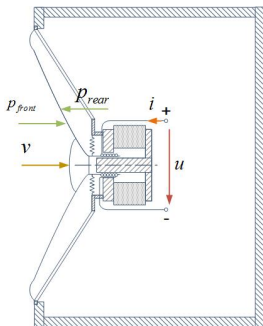
- Target Impedance
- Optimisation of Multiple Degree-of-Freedom Target Impedance

3

Performance Evaluation

- Objective Evaluation

General description



Mobile equipment: M_{ms} , R_{ms} , C_{ms}

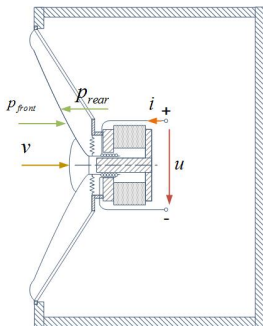
Moving coil: R_e , L_e

Electrodynamic transduction: $B\ell$

Enclosure: V_b

Diaphragm area: S_d

General description



Mobile equipment: M_{ms} , R_{ms} , C_{ms}

Moving coil: R_e , L_e

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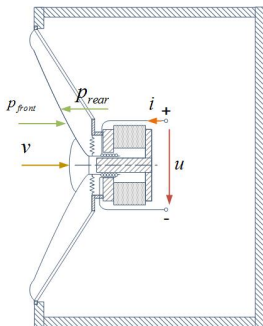
Newton's law on the mobile equipment

$$M_{ms} \frac{dv(t)}{dt} = S_d(p_{front}(t) - p_{rear}(t)) - B\ell i(t) - R_{ms}v(t) - \frac{1}{C_{ms}} \int v(t)dt \quad (1)$$

Mesh law on the electric circuit

$$u(t) = \left(L_e \frac{di(t)}{dt} + R_e i(t) \right) - B\ell v(t) \quad (2)$$

General description



Mobile equipment: M_{ms} , R_{ms} , C_{ms}

Moving coil: R_e , L_e

Electrodynamic transduction: $B\ell$

Enclosure: V_b

Diaphragm area: S_d

Newton's law on the mobile equipment
(Laplace domain: $s = j\omega$)

$$Z_{ms}(s)V(s) = S_d P_{front}(s) - B\ell I(s) \quad (1)$$

where $Z_{ms}(s) = sM_{ms} + R_{ms} + \frac{1}{sC_{mc}}$

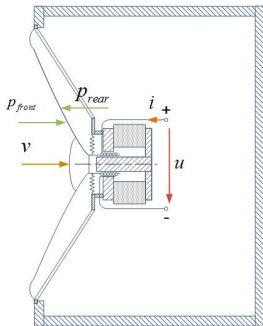
and $C_{mc} = \frac{C_{ms}V_b}{V_b + \rho c^2 S_d^2 C_{ms}}$

Mesh law on the electric circuit
(Laplace domain: $s = j\omega$)

$$U(s) = Z_e(s)I(s) - B\ell V(s) \quad (2)$$

where $Z_e(s) = sL_e + R_e$

General description



Mobile equipment: M_{ms}, R_{ms}, C_{ms}

Moving coil: R_e, L_e

Electrodynamic transduction: $B\ell$

Enclosure: V_b

Diaphragm area: S_d

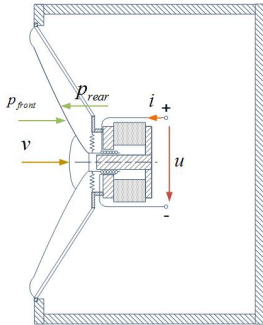
Newton's law on the mobile equipment
(Laplace domain: $s = j\omega$)

$$Z_{ms}(s)V(s) = S_d P_{front}(s) - B\ell I(s) \quad (1)$$

Mesh law on the electric circuit
(Laplace domain: $s = j\omega$)

$$I(s) = \frac{1}{Z_e(s)} (U(s) + B\ell V(s)) \quad (2)$$

General description



Mobile equipment: M_{ms}, R_{ms}, C_{ms}

Moving coil: R_e, L_e

Electrodynamic transduction: $B\ell$

Enclosure: V_b

Diaphragm area: S_d

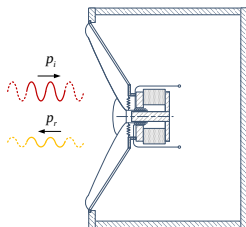
Newton's law on the mobile equipment

$$S_d P_{front}(s) = \left[Z_{ms}(s) + \frac{(B\ell)^2}{Z_e(s)} \right] V(s) + \frac{B\ell}{Z_e} U(s) \quad (1)$$

Diaphragm acoustic impedance

$$Z_s(s) = \frac{P_{front}(s)}{V(s)} = \left[Z_{ms}(s) + \frac{(B\ell)^2}{Z_e(s)} \right] + \frac{B\ell}{Z_e} \frac{U(s)}{V(s)} \quad (2)$$

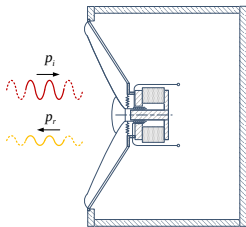
Absorption performance



- Incident pressure p_i
- Reflected pressure

$$p_r = \Gamma(s)p_i = \frac{Z_s(s) - Z_c}{Z_s(s) + Z_c} p_i$$
 (under normal incidence)
- Total pressure $p_{front} = p_i + p_r$

Absorption performance



Sound absorption coefficient

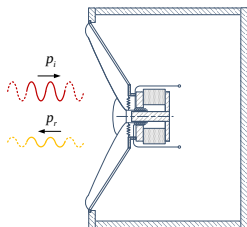
$$\alpha(f) = \frac{I_a}{I_i} = 1 - \left| \frac{Z_s(f) - Z_c}{Z_s(f) + Z_c} \right|^2$$

Bandwidth of efficient sound absorption BW

Frequency range over which $\frac{1}{2} \mathcal{I}_{tot} \leq \mathcal{I}_{ideal\ case}$

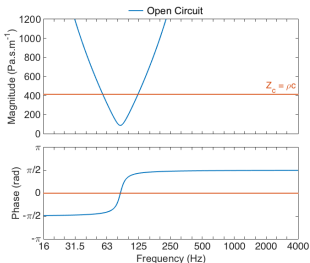
$\rightarrow \alpha_{th} \simeq 0.83$

Absorption performance

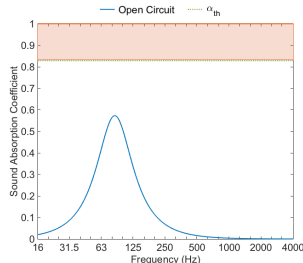


Example: open-circuit loudspeaker ($I = 0$)

$$Z_s(s) = \frac{Z_{ms}(s)}{S_d} = \frac{1}{S_d} \left[sM_{ms} + R_{ms} + \frac{1}{sC_{mc}} \right]$$



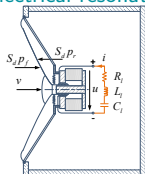
Specific acoustic impedance



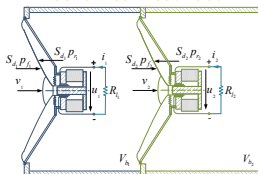
Sound absorption coefficient

Designing Multiple Degree-of-Freedom Resonators

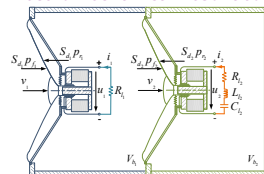
Electrical resonator



Mechanical resonator

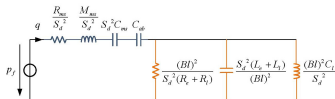


Electromechanical resonator

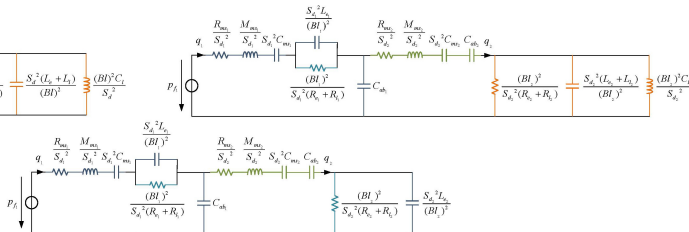


Designing Multiple Degree-of-Freedom Resonators

Electrical resonator



Mechanical resonator



Electromechanical resonator

$$Z_{me1}(s) = \frac{(Bl)^2}{s(L_e + L_l) + R_e + R_l + \frac{1}{sC_l}}$$

$$Z_s(s) = \frac{1}{S_d} [Z_{ms}(s) + Z_{me}(s)]$$

$$Z_{me2}(s) = \frac{(Bl)^2}{Z_{e1} + R_{l1}} + \frac{\left(\frac{S_{d1} S_{d2}}{s C_{ab1}} \right)^2}{Z_{ms2} + S_{d2}^2 \frac{C_{ab1} + C_{ab2}}{s(C_{ab1} C_{ab2})} + \frac{(Bl)^2}{Z_{e2} + R_{l2}}}$$

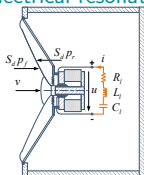
$$C_{ab1,2} = \frac{V_{b1,2}}{\rho c^2}$$

$$Z_{me3}(s) = \frac{(Bl)^2}{Z_{e1} + R_{l1}} + \frac{\left(\frac{S_{d1} S_{d2}}{s C_{ab1}} \right)^2}{Z_{ms2} + S_{d2}^2 \frac{C_{ab1} + C_{ab2}}{s(C_{ab1} C_{ab2})} + \frac{(Bl)^2}{Z_{e2} + R_{l2}}}$$

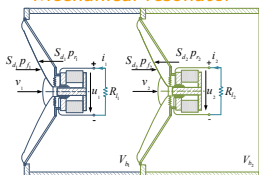
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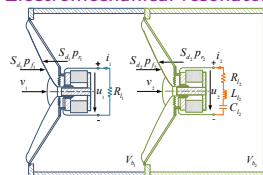
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Mechanical resonator



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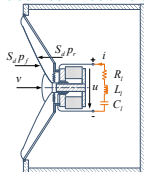


Optimisation strategy

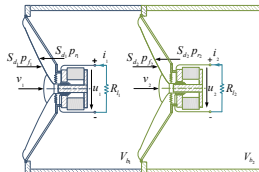
$$\bullet \mathcal{A} = \int \max(\alpha(f) - \alpha_{th}, 0) df$$

Designing Multiple Degree-of-Freedom Resonators

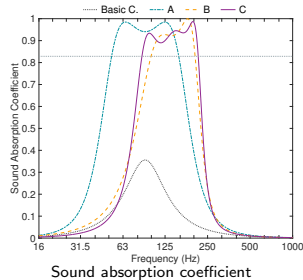
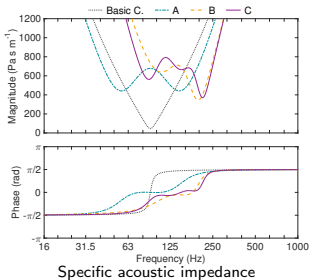
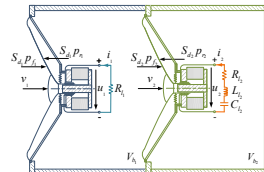
Electrical resonator



Mechanical resonator



Electromechanical resonator



Hybrid Sensor-/Shunt-Based Control

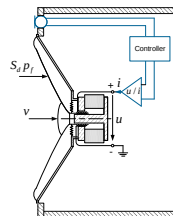
Constitutive laws

$$Z_{ms}(s)V(s) = S_d P_{front}(s) - B\ell I(s)$$

$$I(s) = \Theta(s)P_{front}(s)$$

Acoustic impedance

$$Z_s(s) = \frac{Z_{ms}(s)}{S_d - B\ell\Theta(s)}$$



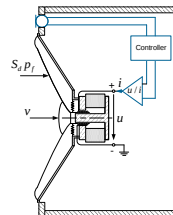
Hybrid Sensor-/Shunt-Based Control

Transfer function

$$\Theta(s) = \frac{I(s)}{P_{front}(s)} = \frac{S_d Z_{st}(s) - Z_m(s)}{B l Z_{st}(s)}$$

Target impedance

$$Z_{st}(s) = s \frac{\mu M_{ms}}{S_d} + R_{st} + \frac{\mu}{s S_d C_{mc}}$$



Rivet et al., *IEEE Transactions on Control Systems Technology*, 2016

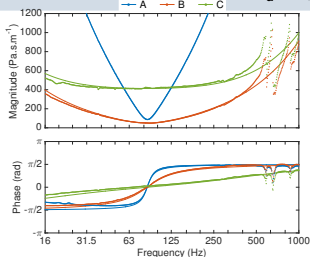
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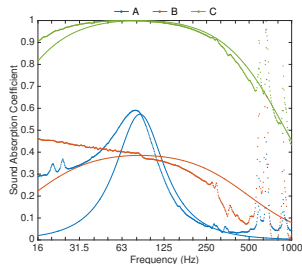
Target impedance

$$Z_{st}(s) = s \frac{\mu M_{ms}}{S_d} + R_{st} + \frac{\mu}{s S_d C_{mc}}$$



Sound absorption coefficient

Case	μ	R_{st}
A	1	R_{ms}/S_d
B	0.15	$\rho c/8$
C	0.15	ρc

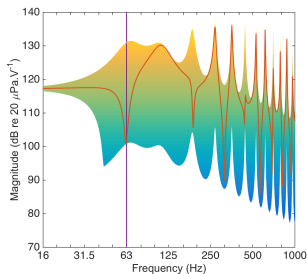
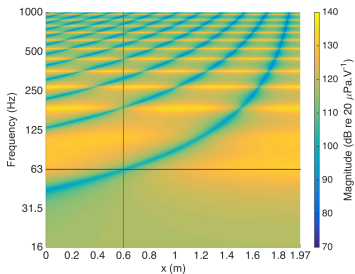
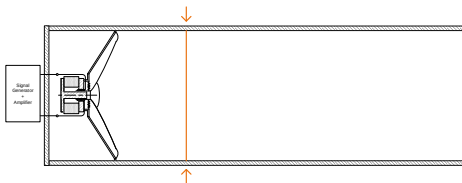


Specific acoustic impedance

Rivet et al., *IEEE Transactions on Control Systems Technology*, 2016

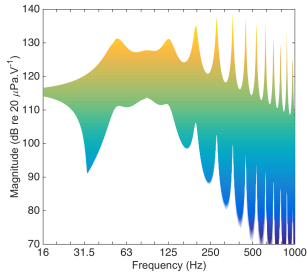
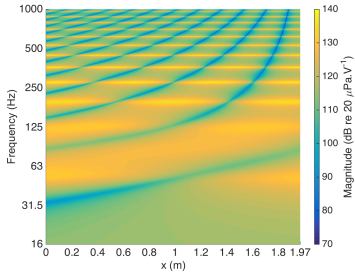
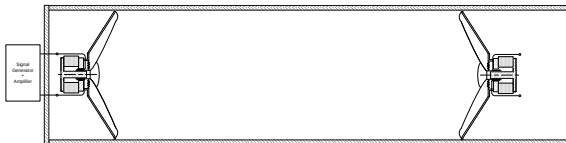
Modal Equalisation in 1D Case

With Hard Wall



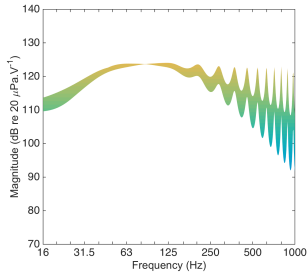
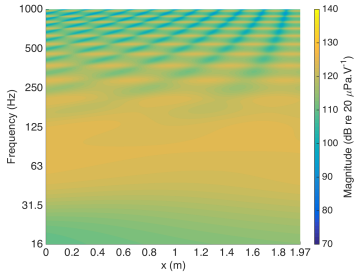
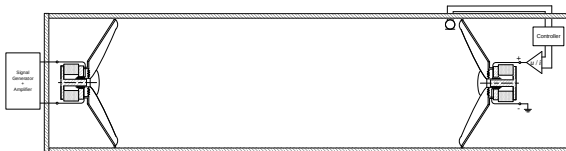
Modal Equalisation in 1D Case

With a Loudspeaker



Modal Equalisation in 1D Case

With an Electroacoustic Absorber



1 Control Design

- Electroacoustic absorbers
- Modal Equalisation in 1D Case

2 Optimisation

- Target Impedance
- Optimisation of Multiple Degree-of-Freedom Target Impedance

3 Performance Evaluation

- Objective Evaluation

1D Case under Normal Incidence

Duct dimensions: $L = 1.7$ m, $W = H = 30$ cm

Target acoustic resistance: $R_s = \zeta \rho c$

1D Case under Normal Incidence

Target acoustic resistance varies with effective absorption area

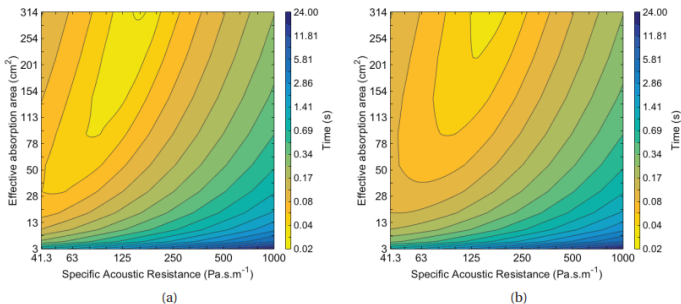
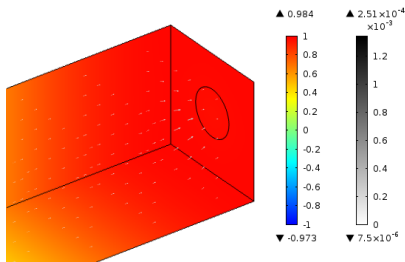
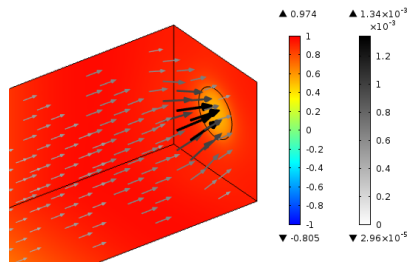


Figure – Specific acoustic resistance – effective absorption area maps of the modal decay times of the (a) mode 1, (b) mode 2, computed for an absorber under normal incidence

1D Case under Normal Incidence



$$R_s = \rho c$$

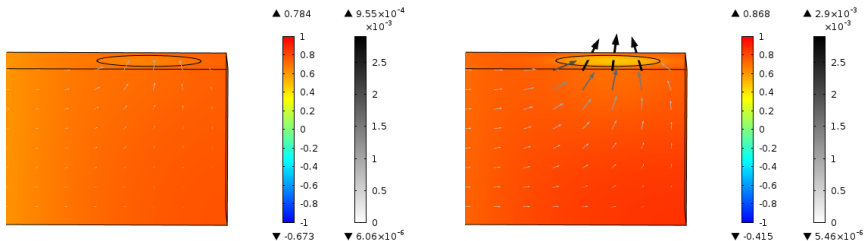


$$R_s = 0.15 \rho c$$

$$r_{abs} = 6 \text{ cm}, S_{abs} = 113 \text{ cm}^2 \text{ (12.6 \% of the wall area)}$$

Sound pressure (color), active sound intensity (gray)

1D Case under Grazing Incidence



$$R_s = \rho c$$

$$R_s = 0.32 \rho c$$

$$r_{abs} = 10 \text{ cm}, S_{abs} = 314 \text{ cm}^2$$

Sound pressure (color), active sound intensity (gray)

In rooms?

- Design of demonstration prototypes

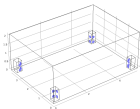


→ Value of target impedance?

Optimization on Modal Decay Time

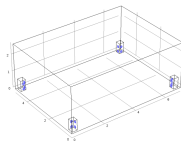
Small room S

$L = 5.33\text{m}, W = 3.76\text{m}, H = 2.13\text{m}$



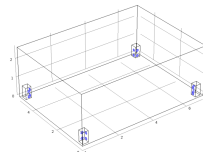
Medium room M1

$L = 7.02\text{m}, W = 5.10\text{m}, H = 2.70\text{m}$



Medium room M2

$L = 7.87\text{m}, W = 6.36\text{m}, H = 3.48\text{m}$



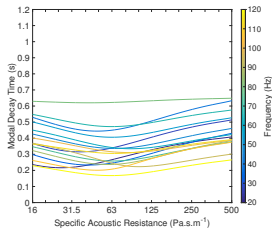
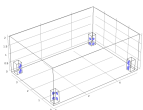
Modal decay time of mode n

$$MT_{60_n} = \frac{3 \ln(10)}{\delta_n}$$

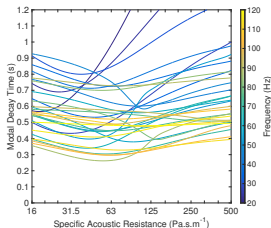
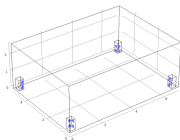
Target Impedance

Modal Decay Time

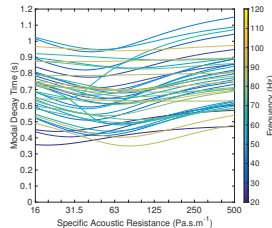
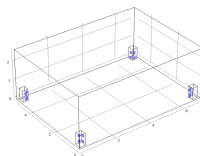
Small room S

 $L = 5.33\text{m}, W = 3.76\text{m}, H = 2.13\text{m}$


Medium room M1

 $L = 7.02\text{m}, W = 5.10\text{m}, H = 2.70\text{m}$


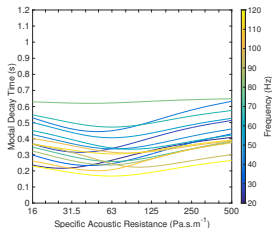
Medium room M2

 $L = 7.87\text{m}, W = 6.36\text{m}, H = 3.48\text{m}$


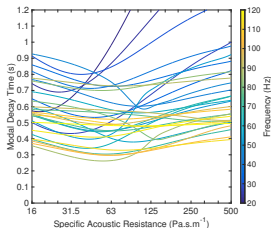
Target Impedance

Modal Decay Time

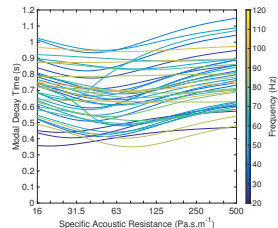
Small room S



Medium room M1



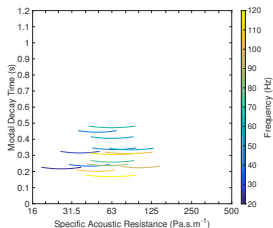
Medium room M2



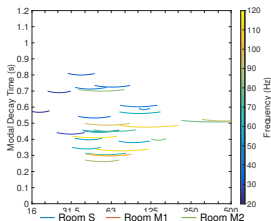
Target Impedance

Modal Decay Time

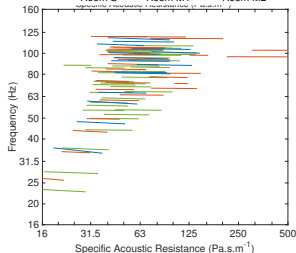
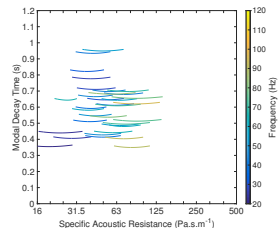
Small room S



Medium room M1



Medium room M2



Active Sound Intensity

Mode (1,0,0) with $R_{s_{abs}} = \zeta \rho c$ Sound pressure (color), active sound intensity (gray)

Design

Multiple degree-of-freedom target impedance

$$Z_{stn-DOF}(\omega) = \frac{1}{\sum_{k=1}^n \frac{1}{Z_{st_k}(\omega, \nu_{2k-1}, R_{st_{2k-1}}, \nu_{2k})}}$$

where

$$Z_{st_k}(\omega, \nu_{2k-1}, R_{st}, \nu_{2k}) = j\omega \frac{M_{ms}}{S_d \nu_{2k-1}} + R_{st} + \frac{1}{j\omega S_d \nu_{2k} C_{mc}}$$

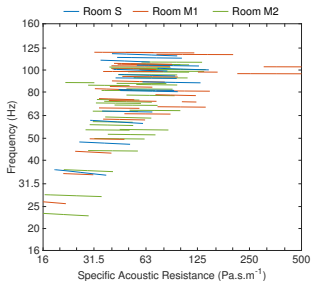
with conditions

$$\nu_1 = \nu_{M_1} - \sum_{k=2}^n \nu_{2k-1} \quad \text{and} \quad \nu_{2n} = \nu_{C_1} - \sum_{k=1}^{n-1} \nu_{2k}$$

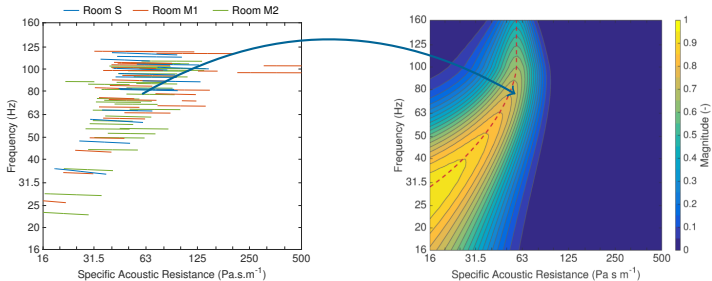
Modified sound absorption coefficient

$$\tilde{\alpha}(R_s, f) = 1 - \left| \frac{Z_s(f) - R_s}{Z_s(f) + R_s} \right|^2$$

Performance Optimisation



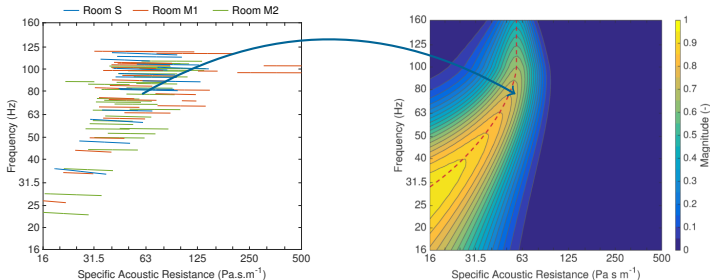
Performance Optimisation



Weighting function of optimal resistances

$$R_{s_{opt}}(R_s, f) = (a_1 f + b_1) \exp \left(- \frac{(R_s - g R_{sp}(f))^2}{2(a_2 f + b_2)} \right)$$

Performance Optimisation



Weighting function of optimal resistances

$$R_{s_{opt}}(R_s, f) = (a_1 f + b_1) \exp \left(-\frac{(R_s - g R_{sp}(f))^2}{2(a_2 f + b_2)} \right)$$

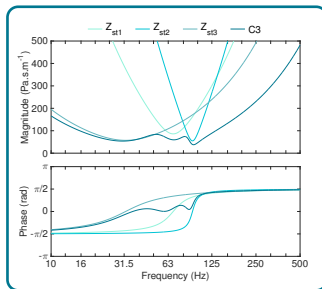
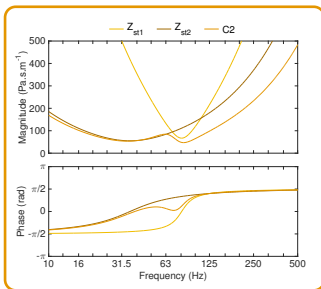
Optimisation strategy

$$\mathcal{A}_2 = \int \int \max(\tilde{\alpha}(R_s, f) - \alpha_{th}, 0) R_{s_{opt}}(R_s, f) dR_s df$$

Optimisation of Multiple Degree-of-Freedom Target Impedance

Performance analysis

$$\frac{Z_{st2-DOF}}{Z_{st1} // Z_{st2}} = (C2)$$

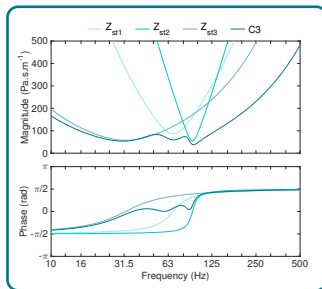
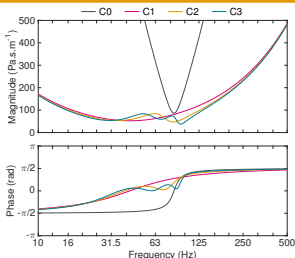
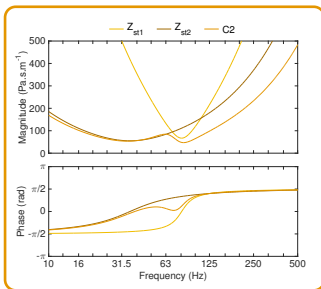


$$\frac{Z_{st3-DOF}}{Z_{st1} // Z_{st2} // Z_{st3}} = (C3)$$

Optimisation of Multiple Degree-of-Freedom Target Impedance

Performance analysis

$$\frac{Z_{st2-DOF}}{Z_{st1} // Z_{st2}} = (C2)$$

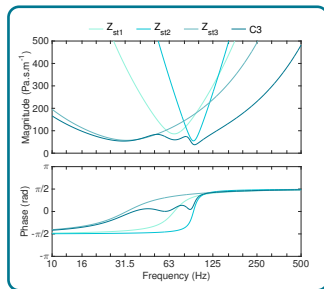
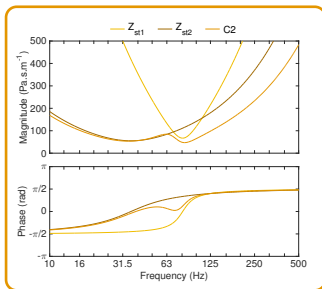


$$\frac{Z_{st3-DOF}}{Z_{st1} // Z_{st2} // Z_{st3}} = (C3)$$

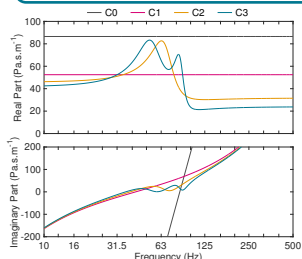
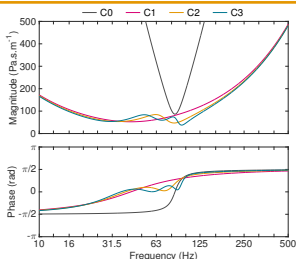
Optimisation of Multiple Degree-of-Freedom Target Impedance

Performance analysis

$$\frac{Z_{st2-DOF}}{Z_{st1}} = \frac{C2}{C1}$$



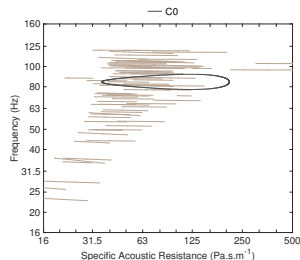
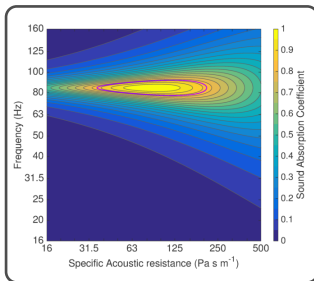
$$\frac{Z_{st3-DOF}}{Z_{st1}} = \frac{C3}{C1}$$



Optimisation of Multiple Degree-of-Freedom Target Impedance

Modified Sound Absorption Coefficient

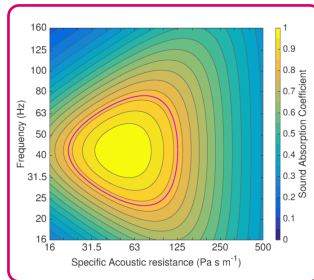
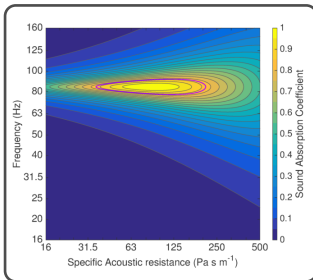
Basic
config.
(C0)



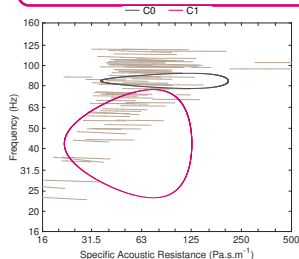
Optimisation of Multiple Degree-of-Freedom Target Impedance

Modified Sound Absorption Coefficient

Basic
config.
(C0)



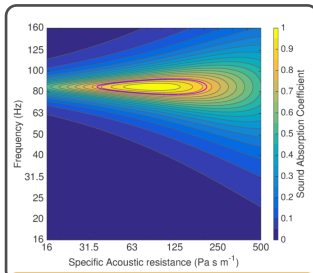
$Z_{st1-DOF}$
(C1)



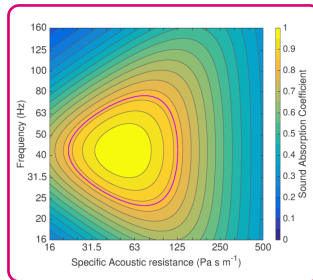
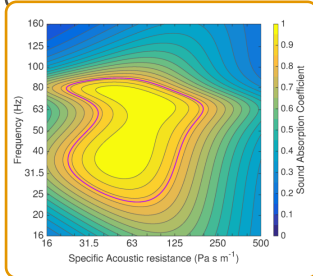
Optimisation of Multiple Degree-of-Freedom Target Impedance

Modified Sound Absorption Coefficient

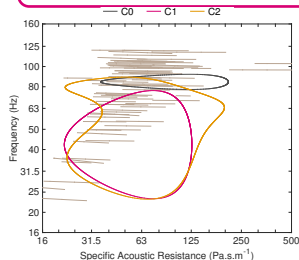
Basic
config.
(C0)



$Z_{st2-DOF}$
(C2)



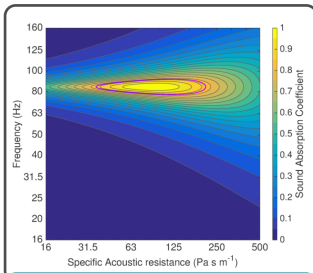
$Z_{st1-DOF}$
(C1)



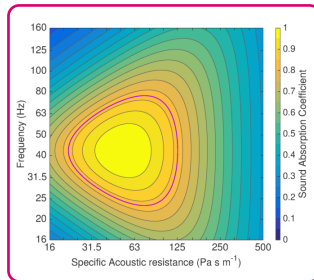
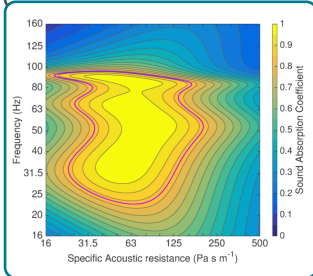
Optimisation of Multiple Degree-of-Freedom Target Impedance

Modified Sound Absorption Coefficient

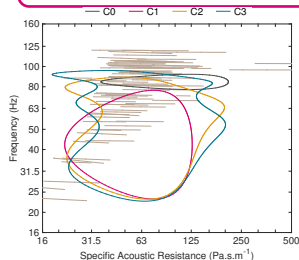
Basic
config.
(C0)



$Z_{st3-DOF}$
(C3)



$Z_{st1-DOF}$
(C1)



1

Control Design

- Electroacoustic absorbers
- Modal Equalisation in 1D Case

2

Optimisation

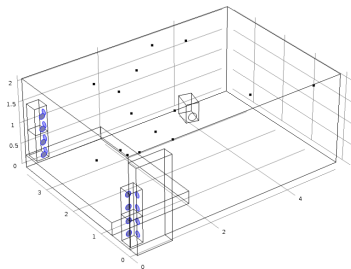
- Target Impedance
- Optimisation of Multiple Degree-of-Freedom Target Impedance

3

Performance Evaluation

- Objective Evaluation

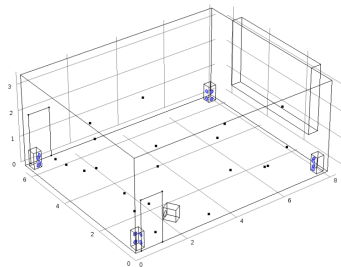
Experimental Setup: Small Room



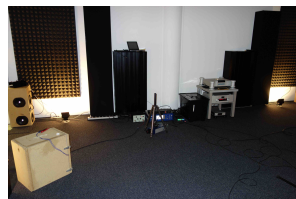
floor area = 20.04 m^2 , volume = 42.69 m^3



Experimental Setup: Medium Room



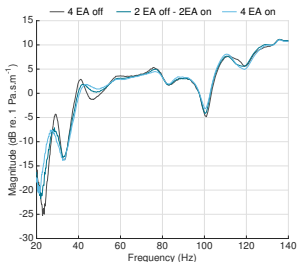
floor area = 50.05 m^2 , volume = 174.18 m^3



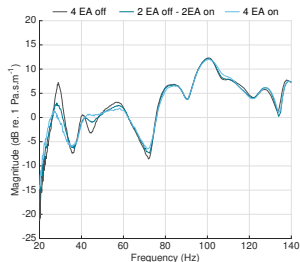
Objective Evaluation

Modal Equalisation: Small Room

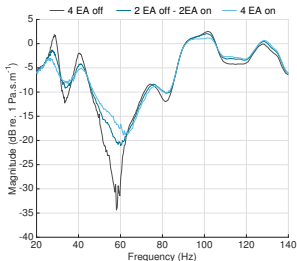
Mic #1



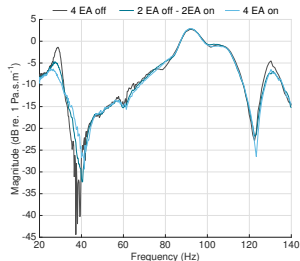
Mic #2



Mic #3



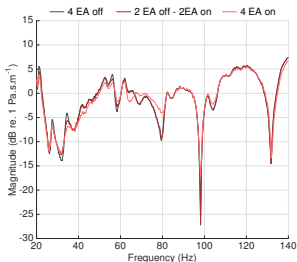
Mic #4



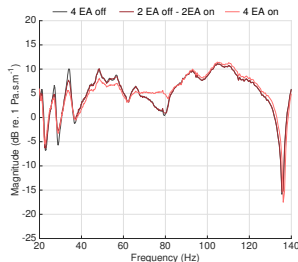
Objective Evaluation

Modal Equalisation: Medium Room

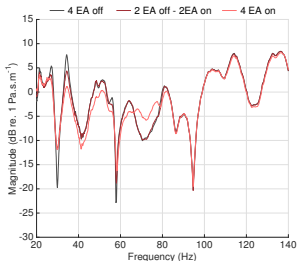
Mic #1



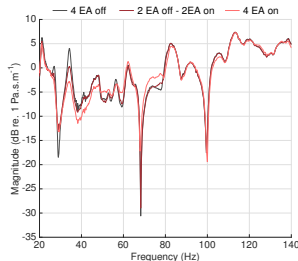
Mic #2



Mic #3



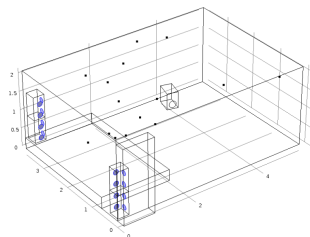
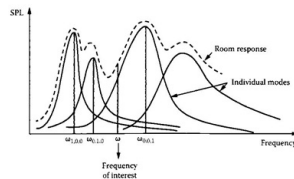
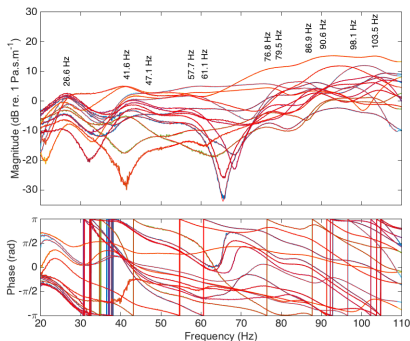
Mic #4



Decrease of Modal Decay Times

Modal decay time of mode n

$$MT_{60n} = \frac{3 \ln(10) Q_n}{\pi f_{0n}}$$



M. H. Richardson, D. L. Formenti, "Global curve fitting of frequency response measurements using the rational fraction polynomial method." *Proceedings of the Third International Modal Analysis Conference*, 1985.

Frequency (MHz)	4 EA off (s)	2 EA off - 2 EA on (s)	4 EA on (s)
23.0	0.67	0.36	0.30
40.4	0.38	0.27	0.24
48.0	0.20	0.20	0.19
53.6	0.32	0.14	0.10
60.8	0.28	0.29	0.26
74.1	0.28	0.24	0.15
77.7	0.26	0.21	0.25
85.2	0.18	0.20	0.20
90.6	0.13	0.14	0.14
98.5	0.20	0.18	0.20
102.7	0.27	0.27	0.27

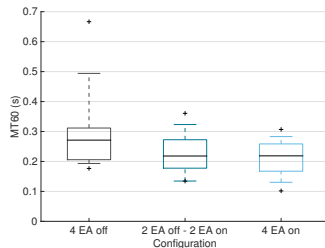
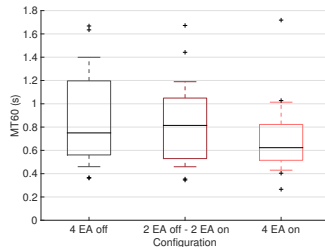


Figure 10: MT60 (s) vs Frequency (Hz) for 2 EA off, 2 EA on, 2 EA on, and 4 EA on. The chart shows that MT60 generally decreases as frequency increases, with the 4 EA on condition consistently showing the highest MT60 values across most frequencies.



Summary of results

- Design guidelines for setting electroacoustic absorbers
 - Impedance control through multiple degree-of-freedom resonators
 - Hybrid sensor-/shunt-based impedance control
- Performance optimisation
 - Definition of new performance metrics
 - Methodology for performance improvement
- Performance evaluation for modal equalisation
 - Development of demonstration prototypes
 - Objective evaluation in real rooms
 - Subjective evaluation of music playback in rooms (not presented here)

Perspectives

- Absorber design
 - Ratio surface/mass
 - Active panels controlled by electrodynamic inertial actuators
 - Development of electroacoustic absorption-diffusion systems
- Performance optimisation
 - Target impedance (reactive terms in simulations)
 - Calibration of electroacoustic absorbers directly in the room
- Performance evaluation
 - Spatial sound field reconstruction (compressive sensing)

Thank you for your Attention

Etienne Rivet PhD Thesis No. 7166

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