DESIGN OF ACTIVE MULTIPLE-DEGREES-OF-FREEDOM ELECTROACOUSTIC RESONATORS FOR USE AS BROADBAND SOUND ABSORBERS

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April 25, 2016

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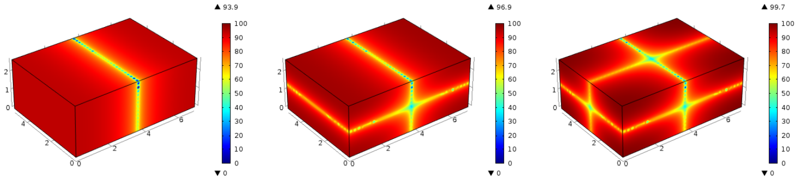
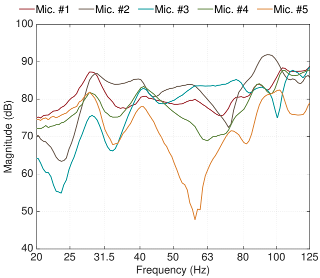
Rooms at Low Frequencies





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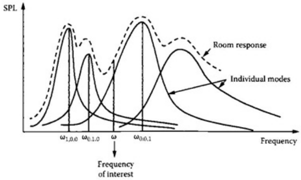
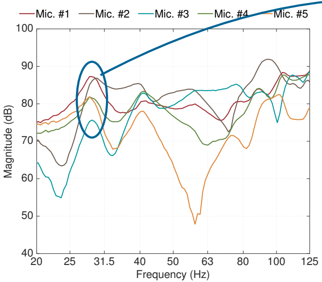
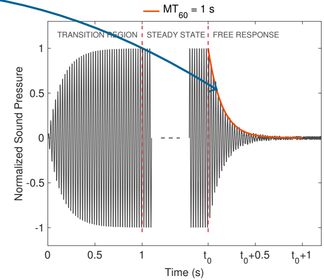


Modal decay time of mode n

$$MT_{60_n} = \frac{3\, ln(10)\, Q_n}{\pi\, f_n}$$

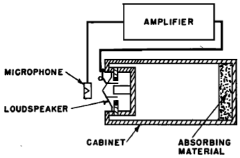




→ How to improve the listening experience in any room at low frequencies?

Correction Strategies

- Active absorption



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

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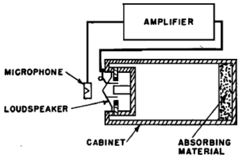

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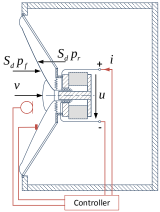
→ Electroacoustic absorbers

Direct



Nicholson, *PhD thesis*, 1994

Correction Strategies

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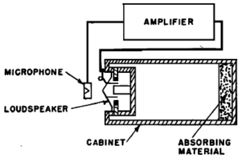

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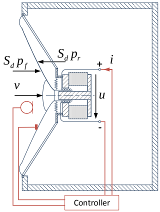
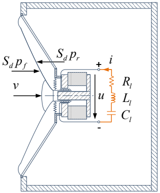


Nicholson, *PhD thesis*, 1994

Shunt-based



Boulandet, *PhD thesis*, 2012

Correction Strategies

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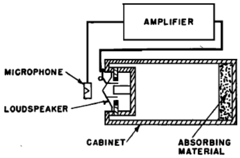

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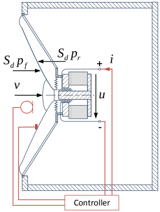

Nicholson, *PhD thesis*, 1994

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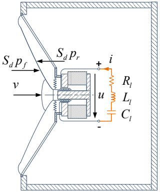
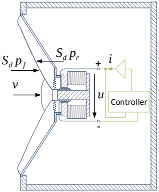


Boulandet, *PhD thesis*, 2012

Self-sensing



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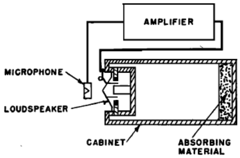

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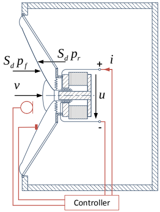

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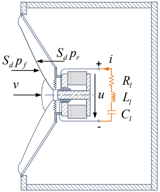

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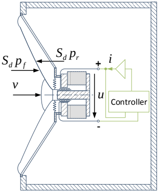
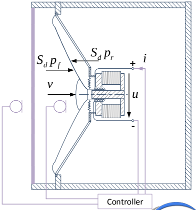


Boulandet, *PhD thesis*, 2012

Hybrid passive/active



Galland et al., *Applied Acoustics*, 2005

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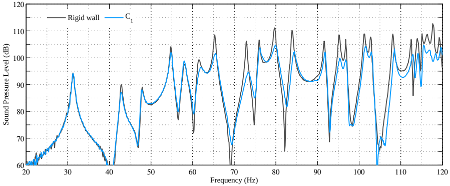
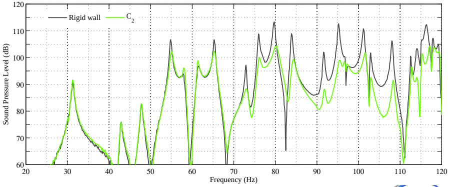
Motivation

- Preliminary experiment with sensorless ("self-sensing") electroacoustic absorbers in a lightly damped room
  R. Boulandet, Tunable electroacoustic resonators through active impedance control of loudspeakers, *PhD thesis No. 5331*, Ecole polytechnique fédérale de Lausanne (EPFL), 2012.





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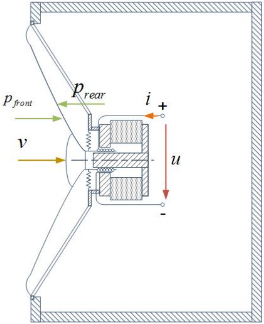
- Good results in highly reverberant conditions (only 0.2 m^2 of active area for 94.3 m^2 of hardwall surfaces)
- However, hardly measurable and audible in conventional listening rooms
  → need to present different acoustic resistances to each modal resonance
- Idea: design passive or active methods to assign multiple target acoustic resistances as a function of frequency
  → Multiple-Degree Of Freedom (MDOF) Electroacoustic Absorbers

General description

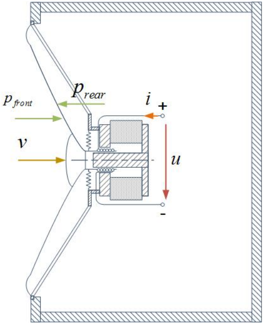


Mobile equipment: M_{ms}, R_{ms}, C_{ms}
Moving coil: R_e, L_e
Electrodynamic transduction: $B\ell$
Enclosure: V_b

Diaphram area: S_d

R. Boulandet, EPFL PhD Thesis 5331, Lausanne (2012)

General description



Mobile equipment: M_{ms}, R_{ms}, C_{ms}
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Newton's law on the mobile equipment (Laplace domain: $s = j\omega$)

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

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

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

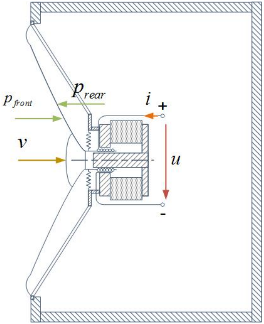
Mesh law on the electric circuit (Laplace domain: $s = j\omega$)

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

where $Z_e(s) = sL_e + R_e$

R. Boulandet, EPFL PhD Thesis 5331, Lausanne (2012)

General description



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

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

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

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

Mobile equipment: M_{ms}, R_{ms}, C_{ms}
Moving coil: R_e, L_e
Electrodynamic transduction: $B\ell$
Enclosure: V_b

Diaphram area: S_d

R. Boulandet, EPFL PhD Thesis 5331, Lausanne (2012)

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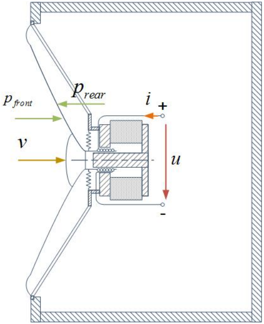


Mobile equipment: M_{ms}, R_{ms}, C_{ms}
Moving coil: R_e, L_e
Electrodynamic transduction: $B\ell$
Enclosure: V_b

Diaphram area: S_d

Newton's law on the mobile equipment

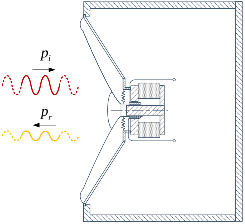
$$S_d P_{front}(s) = \left[Z_{ms}(s) + \frac{(B\ell)^2}{Z_e(s)} \right] V(s) + \frac{B\ell}{Z_e} U(s)$$

Diaphragm acoustic impedance

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

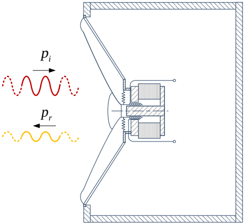
R. Boulandet, EPFL PhD Thesis 5331, Lausanne (2012)

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



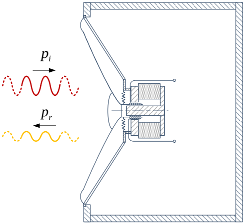
Sound absorption coefficient

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

Bandwidth of efficient sound absorption *BW*

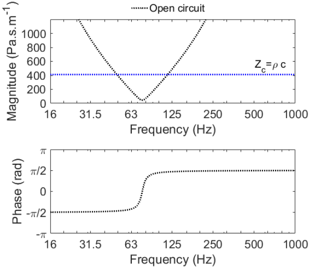
Frequency range over which $\frac{1}{2}\mathcal{I}_{tot} \leq \mathcal{I}_{ideal\ case}$
$\rightarrow \alpha_{th} \simeq 0.83$

Absorption performance

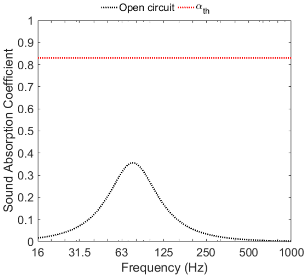


Example: open-circuit loudspeaker ($I = 0$)

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



Specific acoustic impedance



Sound absorption coefficient

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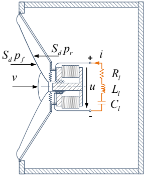
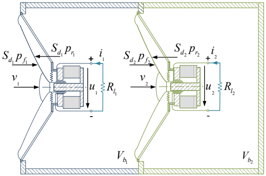
Designing Multiple Degree-of-Freedom Resonators

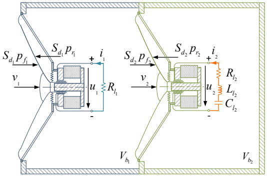
Electrical resonator

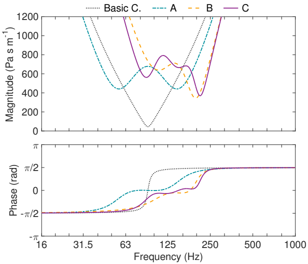


Mechanical resonator

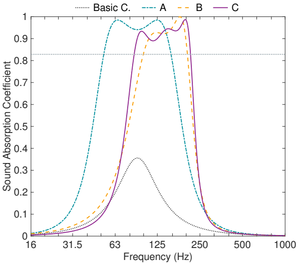


Electromechanical resonator





Specific acoustic impedance



Sound absorption coefficient

E. Rivet, EPFL PhD thesis 7166, Lausanne (2016)

Hybrid Sensor-/Shunt-Based Control

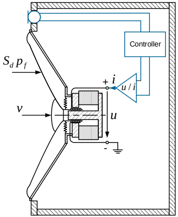
Constitutive laws

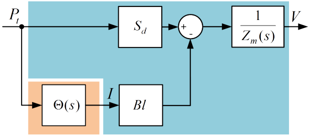
$$Z_{ms}(s)V(s) = S_d P_{front}(s) - B\ell I(s)$$

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

Acoustic impedance

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





Rivet et al., *IEEE Transactions on Control Systems Technology*, 2017

Active 1DOF Electroacoustic Absorber

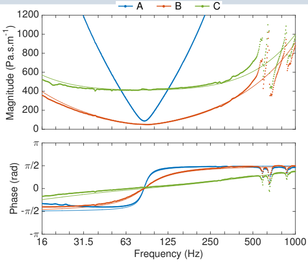
Transfer function

$$\Theta(s) = \frac{I(s)}{P_{front}(s)} = \frac{S_d}{B\ell}\left(1 - \frac{Z_{ms}(s)}{S_d Z_{st}(s)}\right)$$

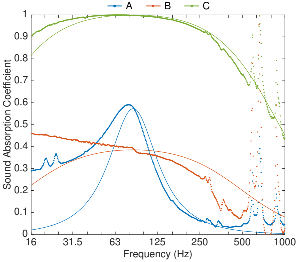
Target impedance

$$Z_{st}(s) = s\frac{M_{ms}}{S_d \nu_1} + R_{st} + \frac{1}{s S_d \nu_2 C_{mc}}$$

Case	$\nu_1 = \nu_2$	R_{st}
A	1	R_{ms}/S_d
B	6	$\rho c/8$
C	6	ρc



Sound absorption coefficient



Specific acoustic impedance

Rivet et al., *IEEE Transactions on Control Systems Technology*, 2017

Active MDOF Electroacoustic Absorber

Transfer function

$$\Theta(s) = \frac{I(s)}{P_{front}(s)} = \frac{S_d}{B\ell}\left(1 - \frac{Z_{ms}(s)}{S_d Z_{st_{nDOF}}(s)}\right)$$

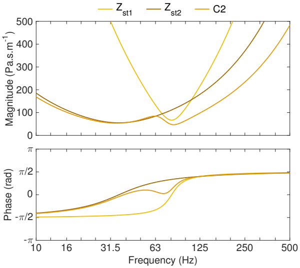
MDOF target impedance

$$Z_{st_{nDOF}}(s) = \frac{1}{\sum_{k=1}^{n} \frac{1}{s\frac{M_{ms}}{S_d \nu_{2k-1}} + R_{st_k} + \frac{1}{s\, S_d \nu_{2k} C_{mc}}}}$$

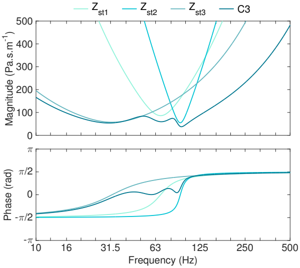
- R_{st_k}: target acoustic resistances
- ν_i: real coefficients, allowing adjusting the resonance frequency of each 1DOF impedance in the summation.

Simulations

$Z_{st_2-DOF} = Z_{st_1} // Z_{st_2}$ (C2)



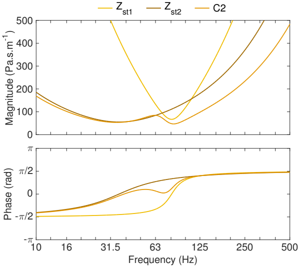
$Z_{st_3-DOF} = Z_{st_1} // Z_{st_2} // Z_{st_3}$ (C3)



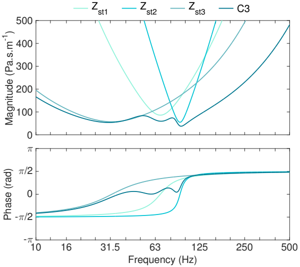
	Z_{st_1}			Z_{st_2}			Z_{st_3}		
	ν_1 (-)	R_{st_1} (Pa·s·m^{-1})	ν_2 (-)	ν_3 (-)	R_{st_2} (Pa·s·m^{-1})	ν_4 (-)	ν_5 (-)	R_{st_3} (Pa·s·m^{-1})	ν_6 (-)
C0	1.00	R_{ms}/S_d	1.00	-	-	-	-	-	-
C1	6.25	52.20	25.00	-	-	-	-	-	-
C2	2.16	67.01	2.36	4.09	55.24	22.64	-	-	-
C3	1.86	85.99	2.86	1.32	54.81	1.11	3.07	57.32	21.03

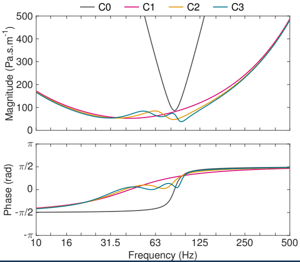
Simulations

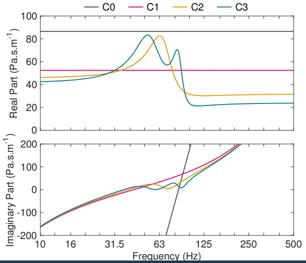
$Z_{st_{2-DOF}} = Z_{st_1} // Z_{st_2}$ (C2)



$Z_{st_{3-DOF}} = Z_{st_1} // Z_{st_2} // Z_{st_3}$ (C3)







Simulations

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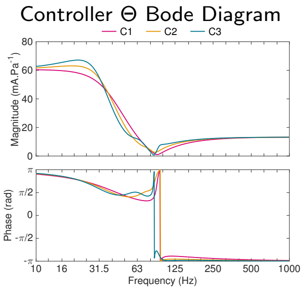
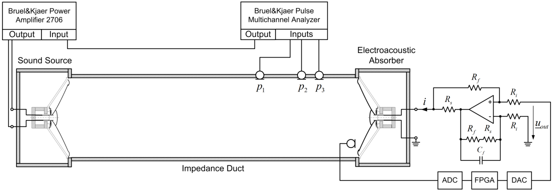
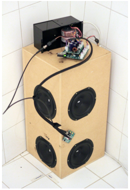
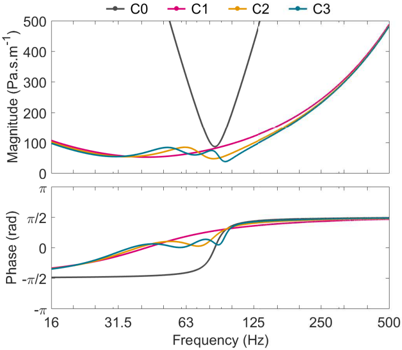


- R_{st_k}: target acoustic resistances
- ν_i: real coefficients, allowing adjusting the resonance frequency of each 1DOF impedance in the summation.

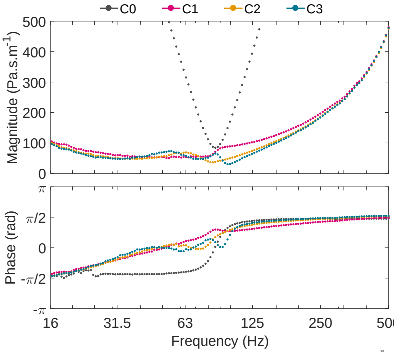
Experimental Setup: Impedance tube (ISO 10534-2 standard)





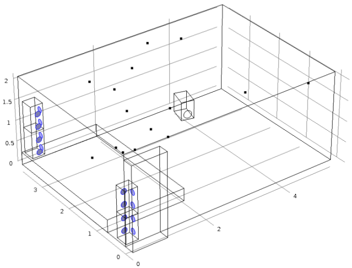


simulations

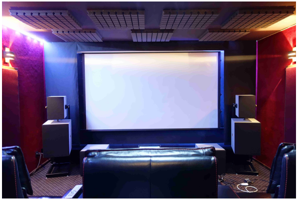


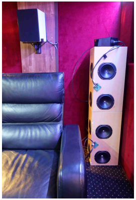
measurements

Experimental Setup: Small Room

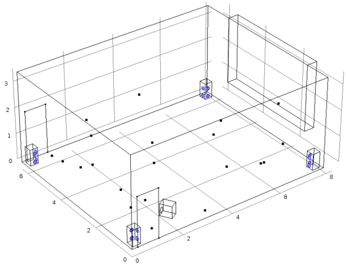


floor area $= 20.04\,\mathrm{m}^2$, volume $= 42.69\,\mathrm{m}^3$

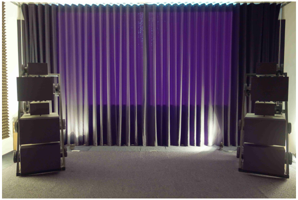


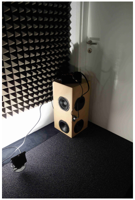


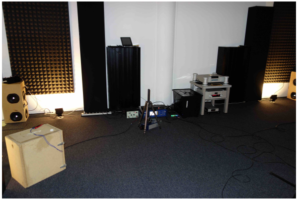
Experimental Setup: Medium Room



floor area $= 50.05\,\mathrm{m}^2$, volume $= 174.18\,\mathrm{m}^3$

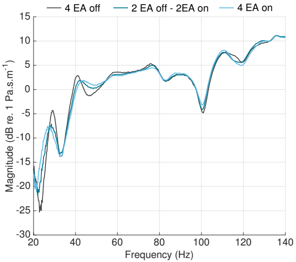




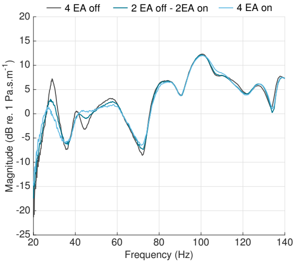


Modal Equalisation: Small Room

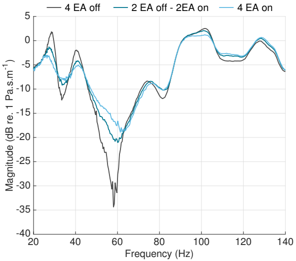
Mic #1



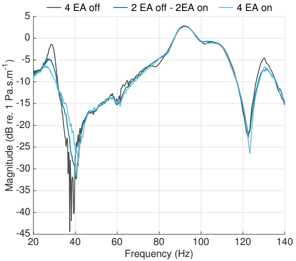
Mic #2



Mic #3

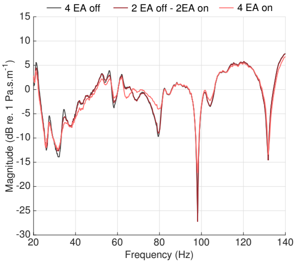


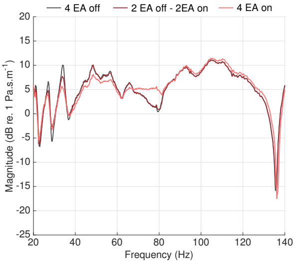
Mic #4



Modal Equalisation: Medium Room

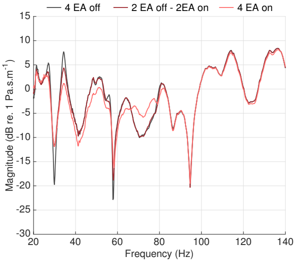
Mic #1

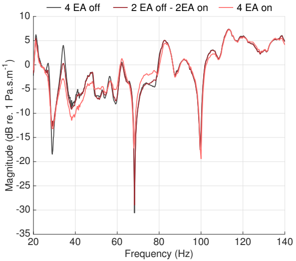




Mic #2

Mic #3



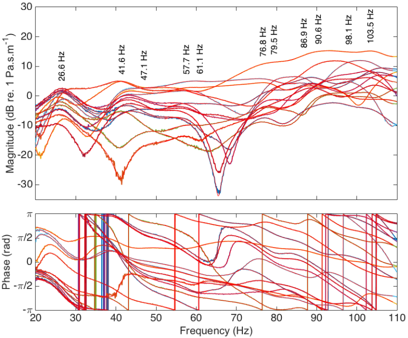


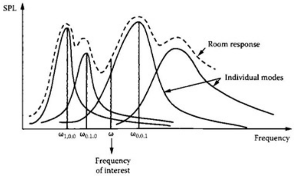
Mic #4

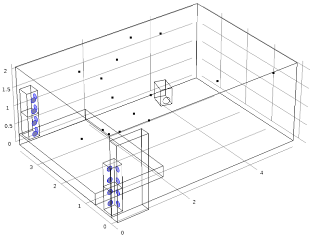
Decrease of Modal Decay Times

Modal decay time of mode n

$$MT_{60_n} = \frac{3\,ln(10)\,Q_n}{\pi\, f_n}$$



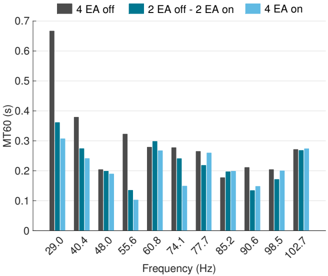


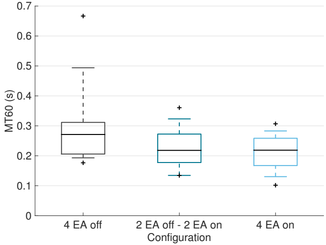


M. H. Richardson, D. L. Formenti, "Global curve fitting of frequency response measurements using the rational fraction polynomial method." *Proceedings of the Third International Modal Analysis Conference*, 1985.

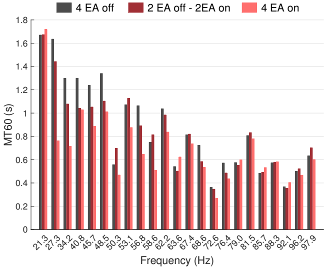
Decrease of Modal Decay Times

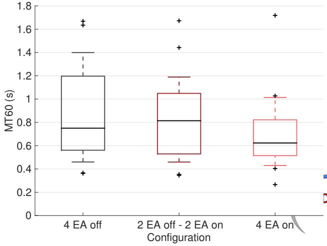
Small room





Medium room



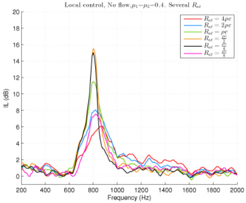


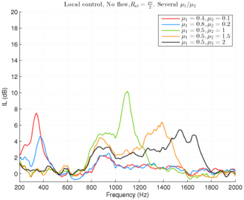
Summary of results

- 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: MT_{60}
  - Specify varying acoustic resistances as a function of frequency (not presented here)
- Performance evaluation for modal equalisation
  - Development of demonstration prototypes
  - Objective evaluation in real rooms
  - Subjective evaluation of music playback in rooms (not presented here)

Other applications

- Ongoing work on active liners for aircraft engine noise reduction
- Assessed array of 3 × 10 small loudspeakers (5 cm × 5 cm × 8 cm)
- Achievement of 15 dB IL at the natural resonance frequency of the loudspeakers
- Possibility to adapt the frequency depending on the aircraft engine regime





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

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  - HEPIA: Haute Ecole du Paysage, d'Ingénierie et d'Architecture (Geneva, Switzerland)
  - Relec S.A. (Yverdon, Switzerland)
  - Goldmund International (Plan-les-Ouates, Switzerland)

- Etienne Rivet PhD Thesis No. 7166 is accessible online https://infoscience.epfl.ch/record/222866