Design of Electroacoustic Absorbers using PID control

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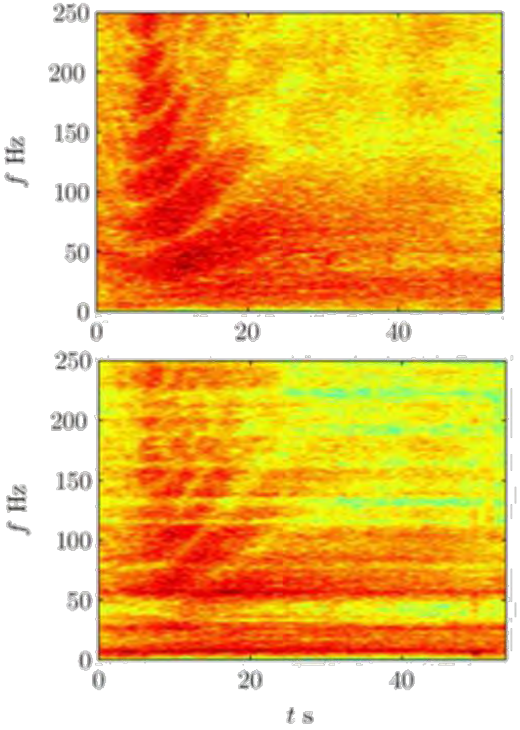
Outline

- Context
- Electroacoustic absorbers
- Design on COMSOL Multiphysics
- Results and validation
- Conclusions and perspectives

CONTEXT

Context

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



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

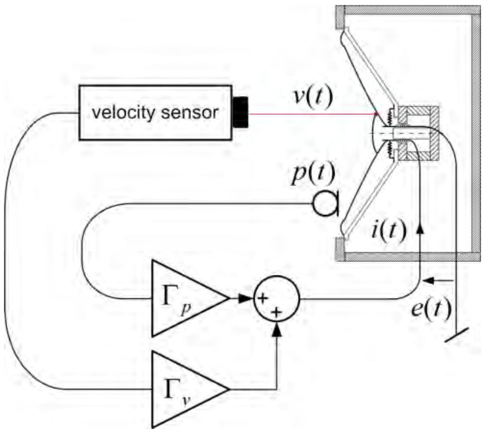
Applications

- residential soundproofing
- industrial machine noise control

- Solution: impedance-based control of loudspeaker such as “**electroacoustic absorbers**”

Context

- Feedback-based techniques

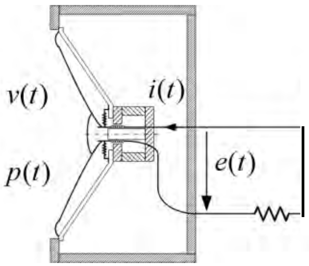


- Direct (proportional) feedback on acoustic quantities

  H.F. Olson, electronic sound absorber, 1953

  E. De Boer, theory of motional feedback, 1961

- Shunt-based techniques



Active shunt
(negative resistance)

Passive shunt
(resistance)

- Passive or active shunt network
- Sensorless control

  R.J. Bobber, active transducer as characteristic impedance, 1970

  A.J. Fleming *et al.*, electrical shunting of a loudspeaker, 2007

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

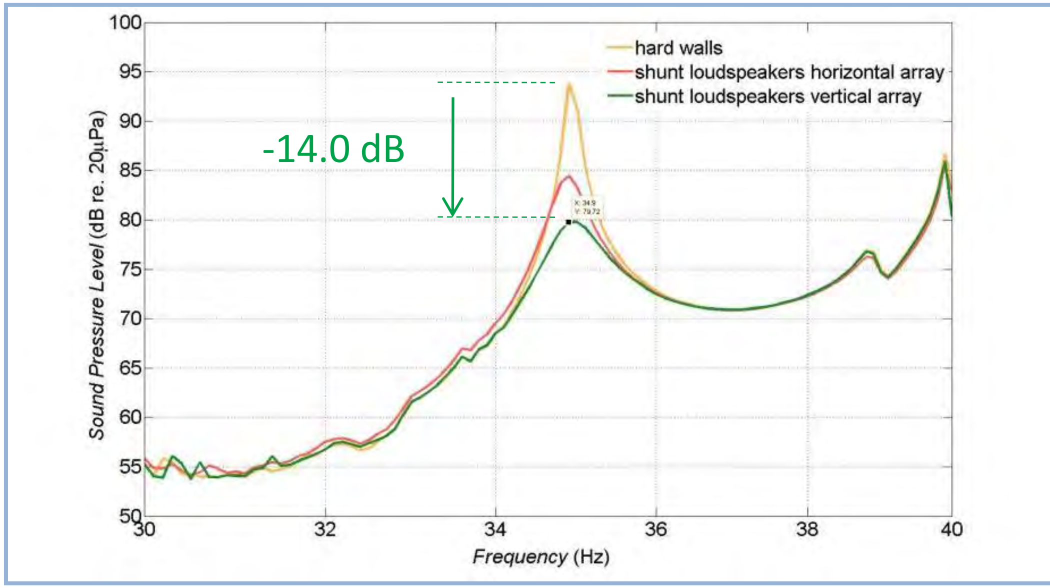
H. Lissek et al., "Shunt loudspeakers for modal control in rooms", Proc. of 16th ICSV, Krakow, Poland (2009)

Example

Damping of rooms' modal behavior

Experimental setup

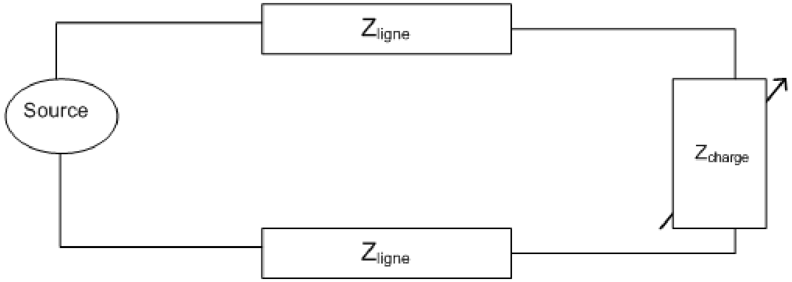
Reverberant chamber at EPFL-LEMA (volume 215.6 m3, tot. surface 226.9 m2)



- 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 dm^3 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

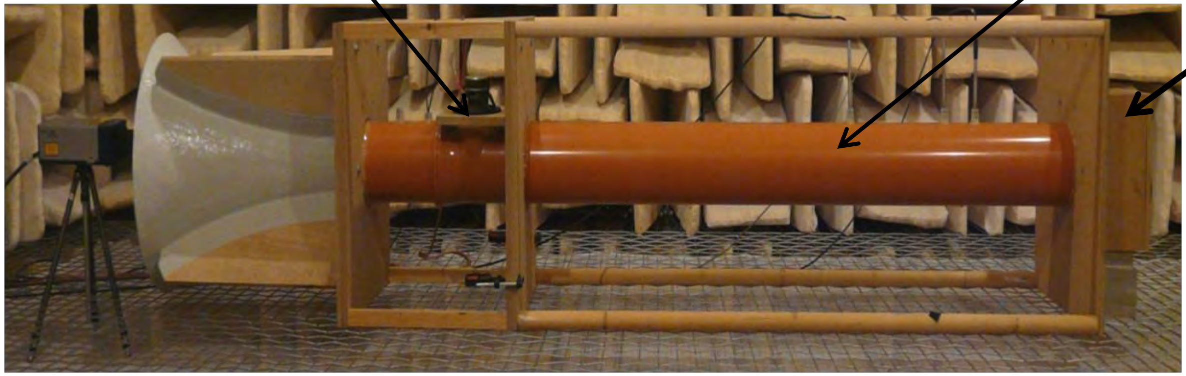


$Z_{\text{load}} = Z_{\text{line}}$ → Total absorption

Source

Line: impédance tube

Load: electroacoustic absorber



$$Z_{\text{line}} = Z_c = \rho c$$

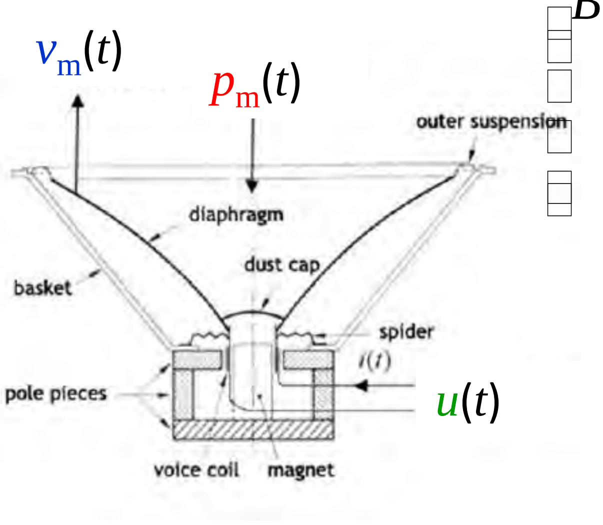
$$Z_{\text{load}} = \frac{p_m(t)}{v_m(t)}$$

$$z_{\text{norm}} = \frac{p_m(t)}{\rho c v_m(t)}$$

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 2nd Newton's law



$$\begin{cases} Bl\,i(t) - S_d\,p_m(t) = R_{ms} v_m(t) + m_s \frac{dv_m(t)}{dt} + \frac{1}{C_{ms}} \int v_m(t)\,dt \\ u(t) = R_e i(s) + L_e \frac{di(t)}{dt} + Bl\,v_m(t) \end{cases}$$

Bl (N.A^{-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
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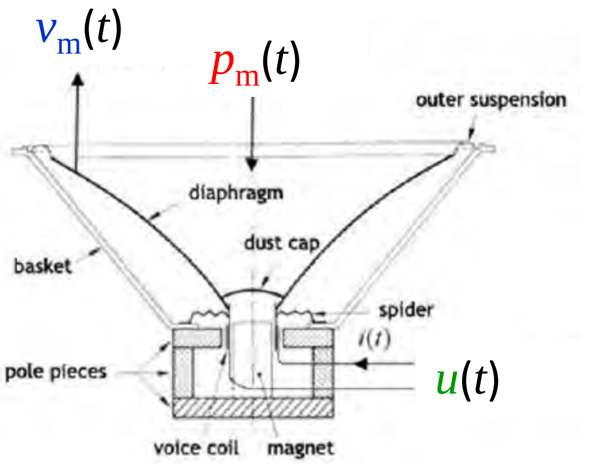


$$\begin{cases} Bl\,i(s) - S_d\,p_m(s) = Z_m v_m(s) \\ u(s) = Z_e\,i(s) + Bl\,v_m(s) \end{cases}$$

$$s = j\omega$$

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

$$\boxed{z_{\mathrm{norm}}(s) = \frac{p_m}{\rho c v_m} = f(s, Z_{ms}, Z_e, Bl, S_d, u)}$$

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

$$z_{\text{norm}} = \frac{p_m}{\rho c v_m} = 1$$

Command law

$$e(t) \square \frac{p_m(t)}{\rho c} - v_m(t)$$

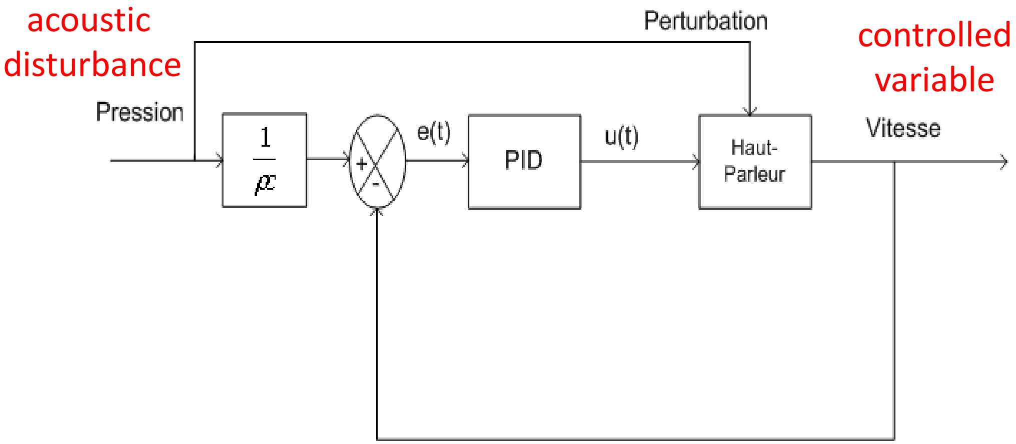
Goal: minimize $e(t)$
yields z_{norm} tends to 1

$p_{\text{m}}(t)$ and $v_{\text{m}}(t)$ measurable
but only $v_{\text{m}}(t)$ is controllable

- Control z_{norm} by feedback

Electroacoustic absorbers
4. PID control

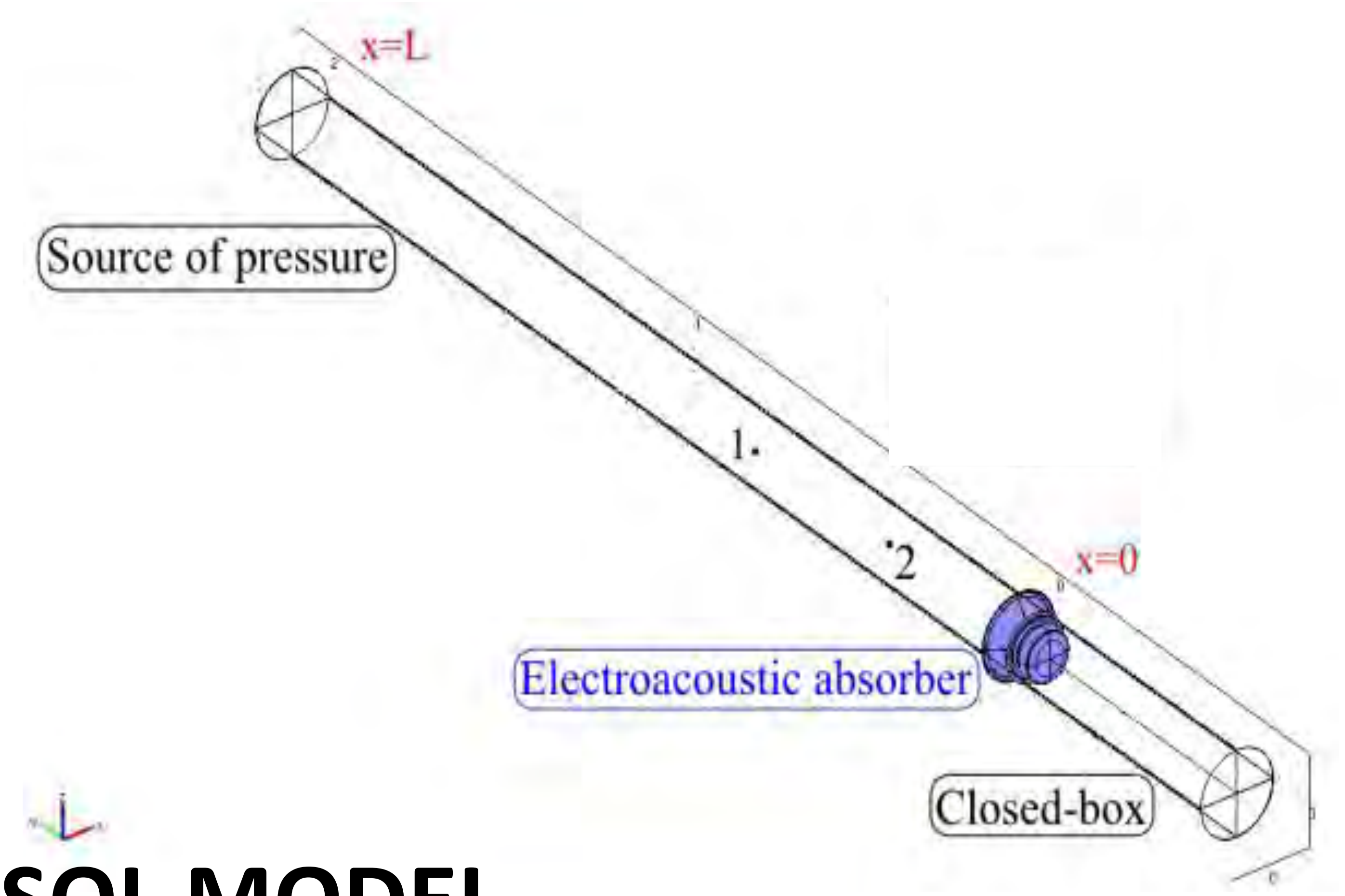
- 2^{nd} order system
- Feeds back the loudspeaker with command voltage $u(t)$ after error signal $e(t)$



proportional gain   integral gain   derivative gain

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

pressure p_m is considered as the **reference**
but it is also the **disturbance**



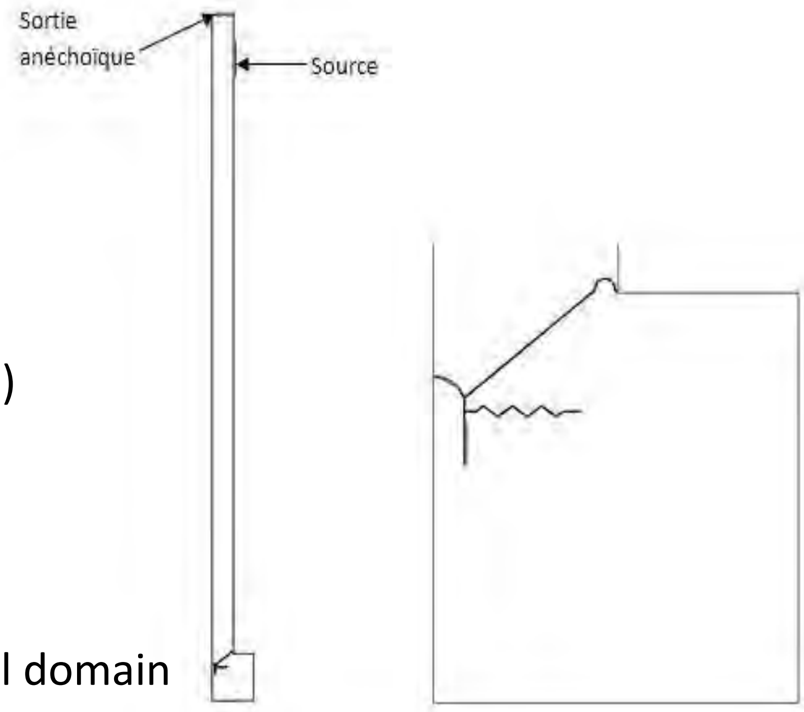
COMSOL MODEL

COMSOL Model
1. General setup

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

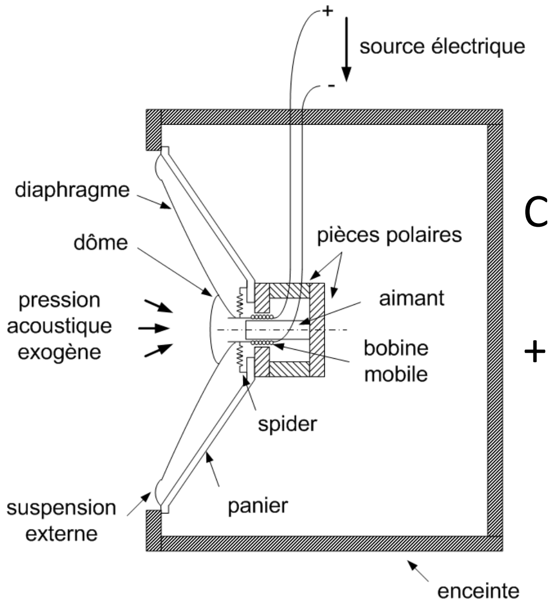
- 2D-axisymetric model
    - Loudspeaker + box (COMSOL Tutorial)
    - Impedance tube
    - PID control

- PID➔Time-domain study
    - More complex than in the frequential domain



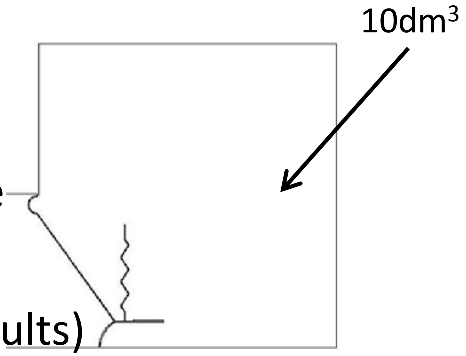
COMSOL Model
2. Electroacoustic absorber

Baseline: COMSOL Tutorial ("Loudspeaker driver")



COMSOL Tutorial example

+ fine tuning (wrt exp. results)



	E (Pa)	ν	ρ (kg m^{-3})	m (g)
dust cap	7e10	0.33	2700	1.1
diaphragm	7e10	0.33	140	0.8
spider	1e7	0.45	215	0.9
outer suspension	1e7	0.45	405	1.2
coil support	3.8e9	0.37	1500	0.6
voice coil	1.1e11	0.30	8700	7.5

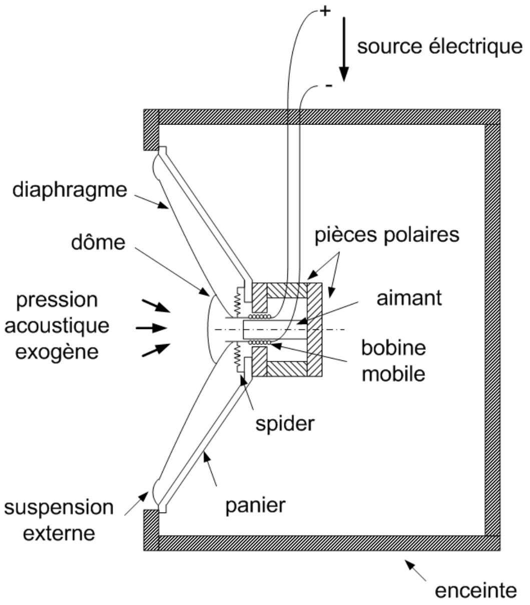
Mechanical parameters modified to fit VISATON®Al170

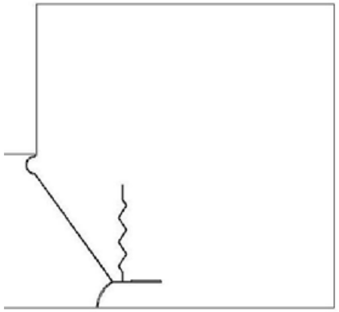
- mass density
- Poisson modulus
- Young modulus

(see Moreau et al. Comsol Conference 2009)

COMSOL Model
2. Electroacoustic absorber

Baseline: COMSOL Tutorial ("Loudspeaker driver")





$(p_{\mathrm{m}}, v_{\mathrm{m}})$ probes ➔ $e(t)$

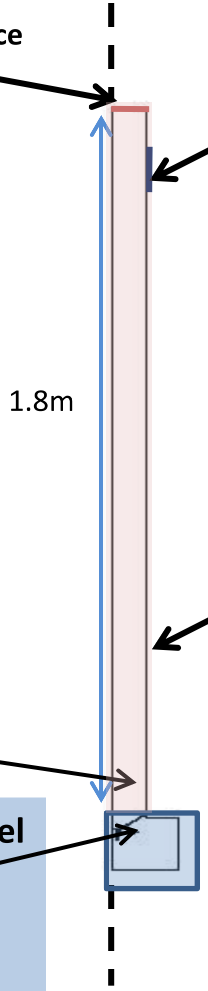
Feedback voltage:

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

Assuming constant Bl

COMSOL Model

3. Waveguide



Anechoic termination
Boundary condition: Impedance
$Z=\rho c$

Axysimetric sound source
Boundary condition: pressure
$p = p_m \sin(2\pi f t),\ f \in [50 - 1000\text{Hz}]$

fluid (air) domain
$\rho=1{,}2\ \text{kg.m}^{-3}$
$c=340\ \text{m.s}^{-1}$

Tube outer wall
Boundary condition
Hardwalls

Measured quantities (air domain)
p_m
v_m

Electroacoustic absorber model
Membrane
+ driver
+ enclosure
+ PID control

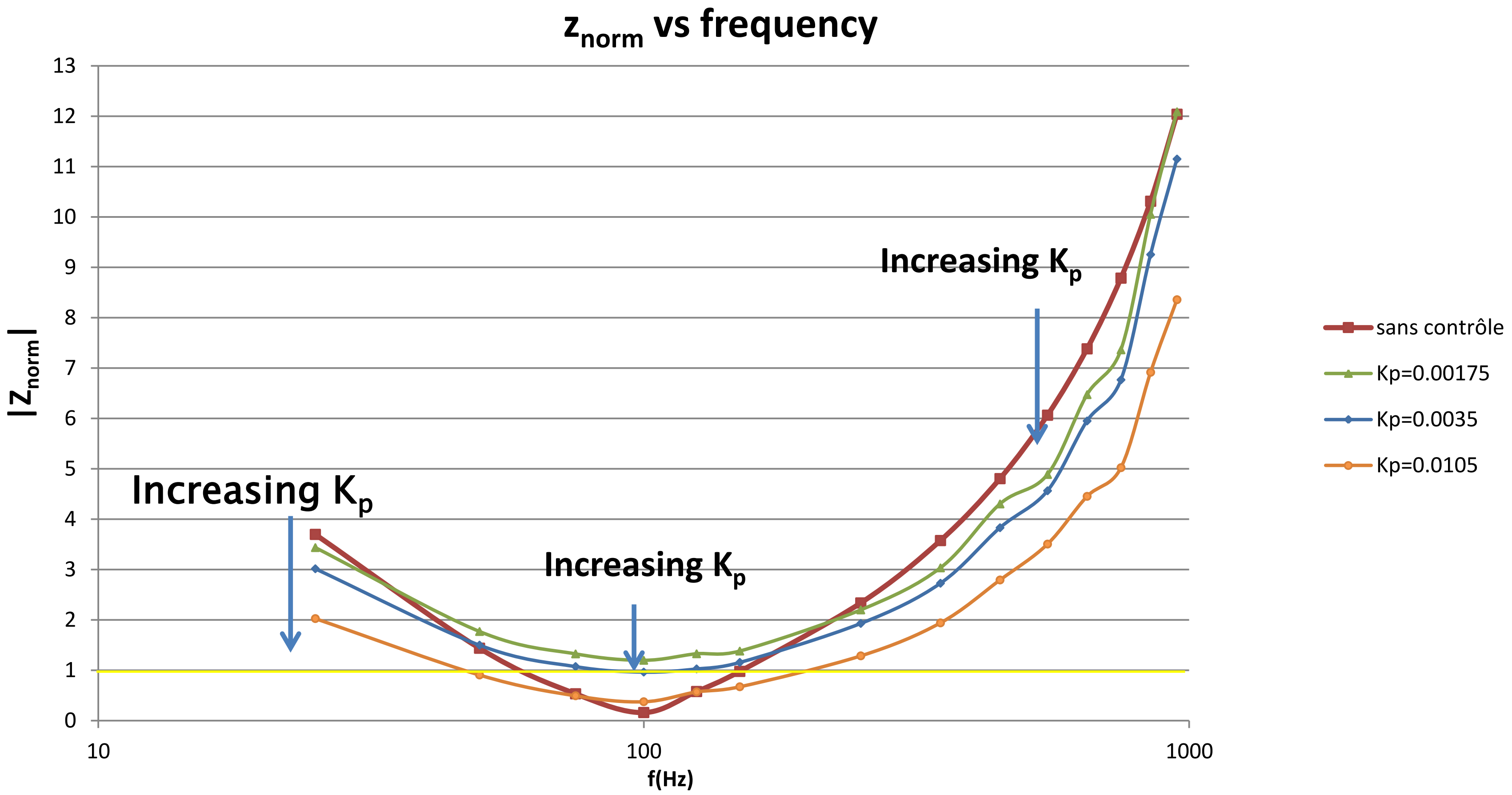
- Max mesh size < $\lambda/5$
- One simulation for each frequency
- Electroacoustic absorber acoustic impedance processed on several periods
- **Output:**

$$z_\text{norm} = \frac{1}{\rho c}\,\frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N} p_{mi}^{2}}}{\sqrt{\frac{1}{N}\sum_{i=1}^{N} v_{mi}^{2}}}$$

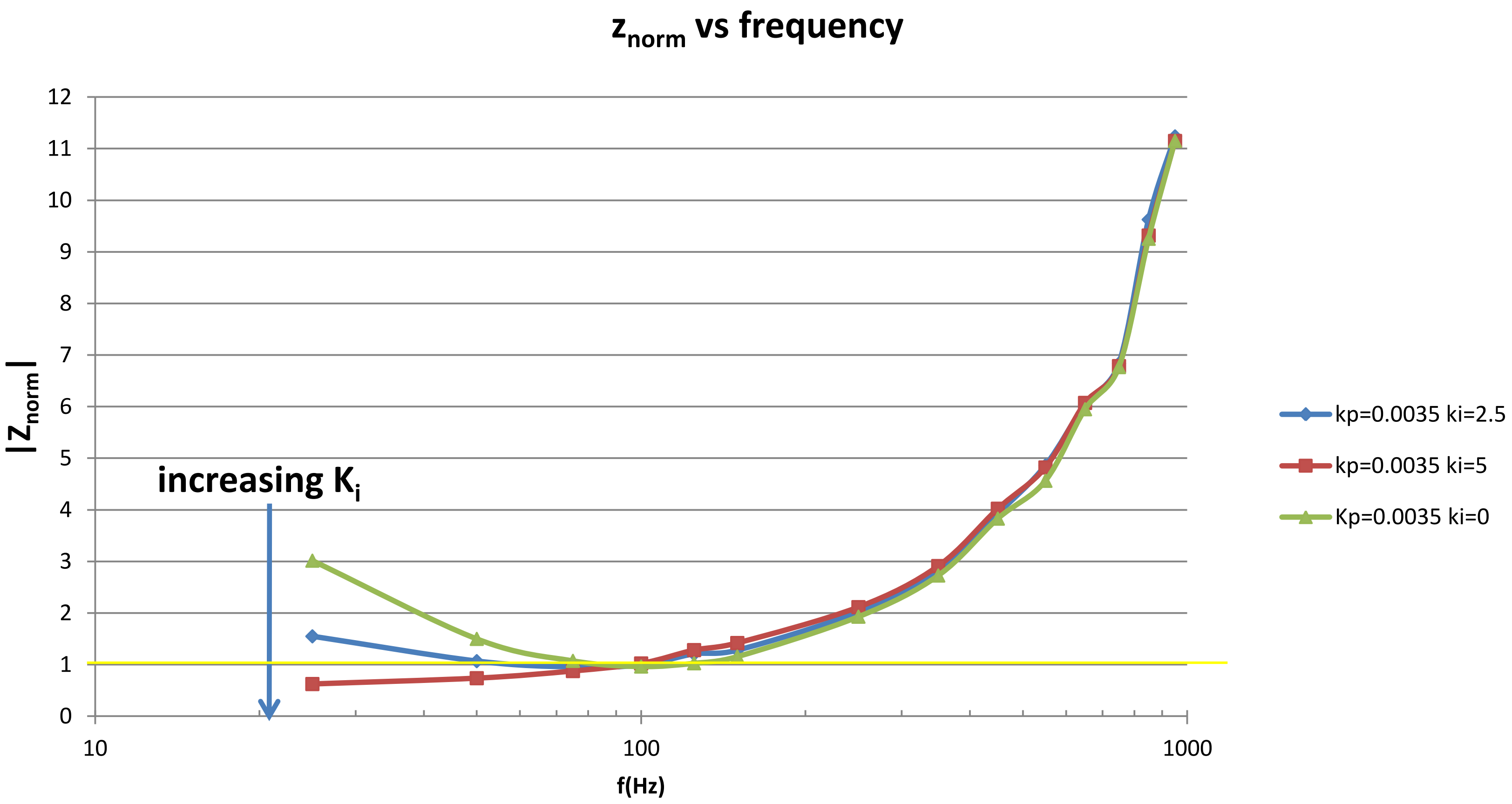
VALIDATION

Validation

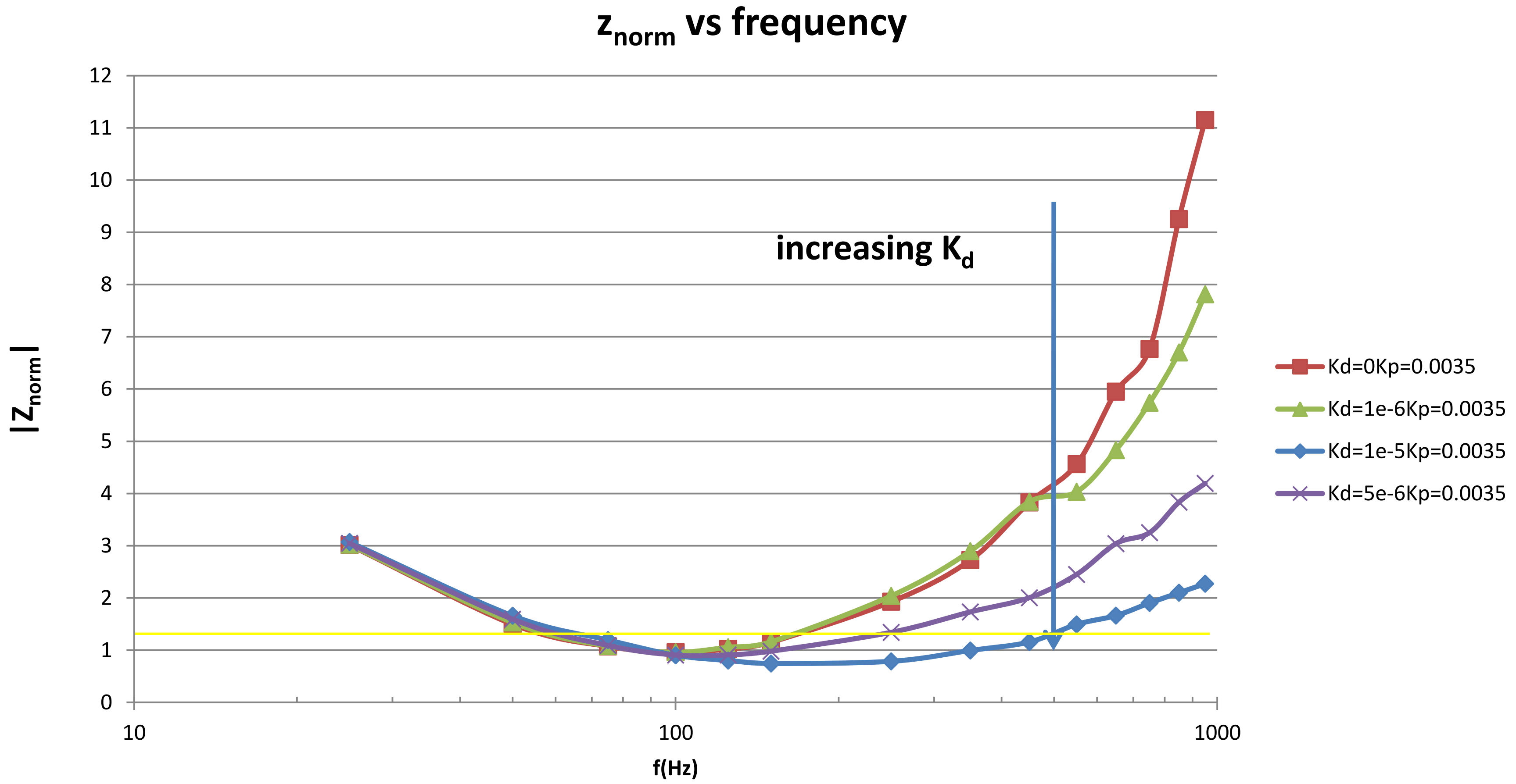
1. Proportional corrector



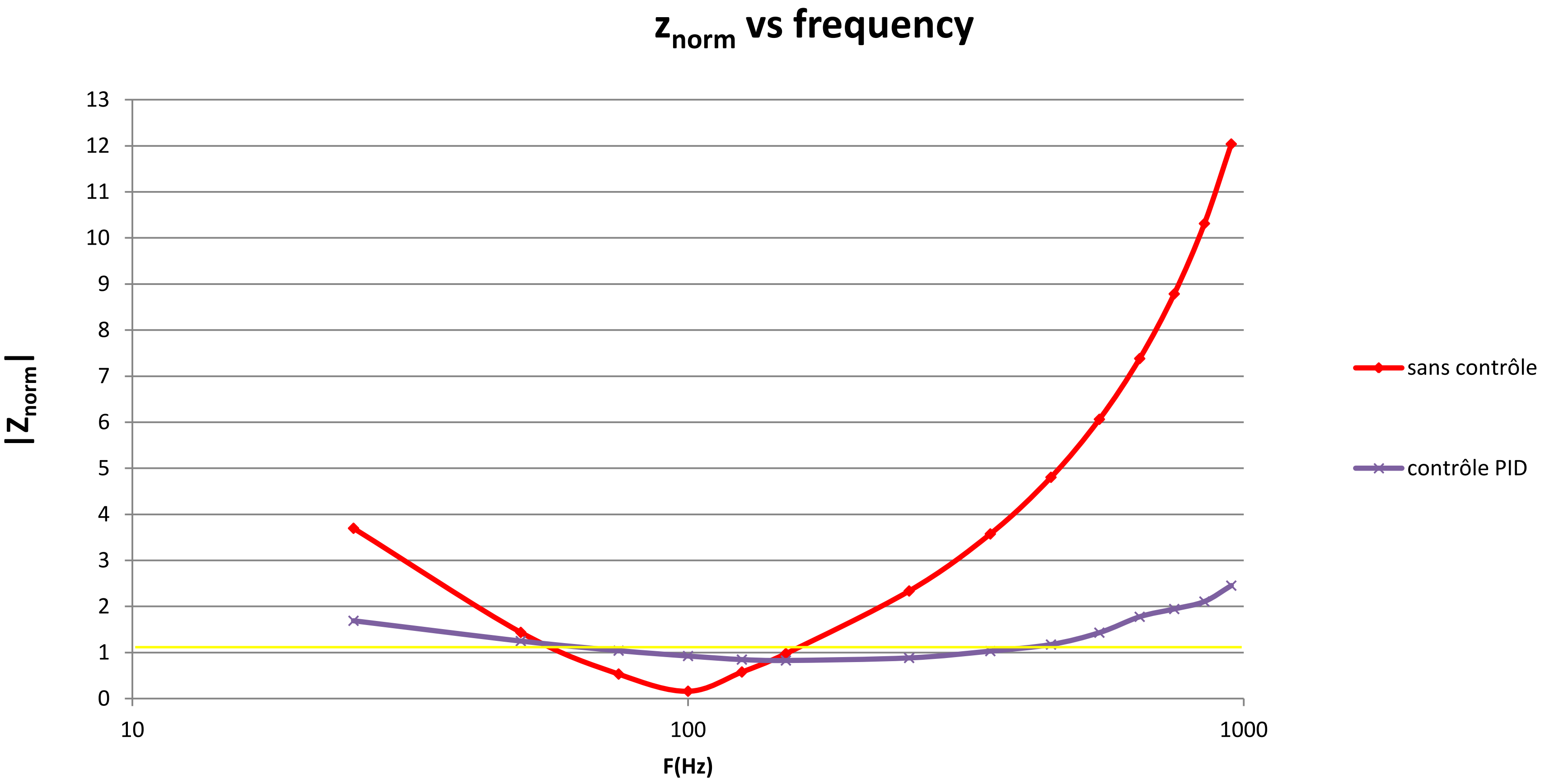
Validation
2. Proportional-Integral corrector



Validation
3. Proportional-integral corrector

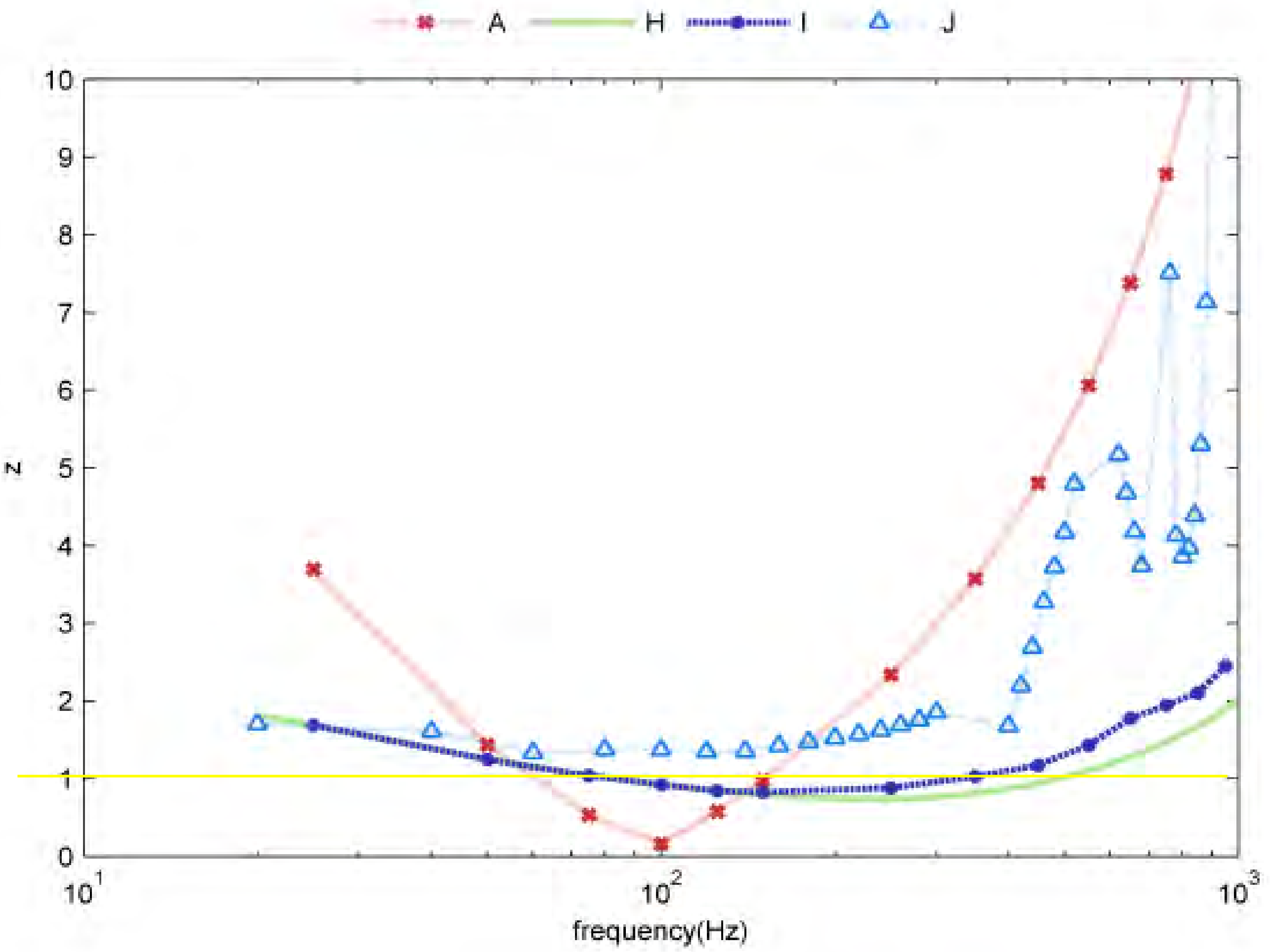


Validation
4. PID corrector

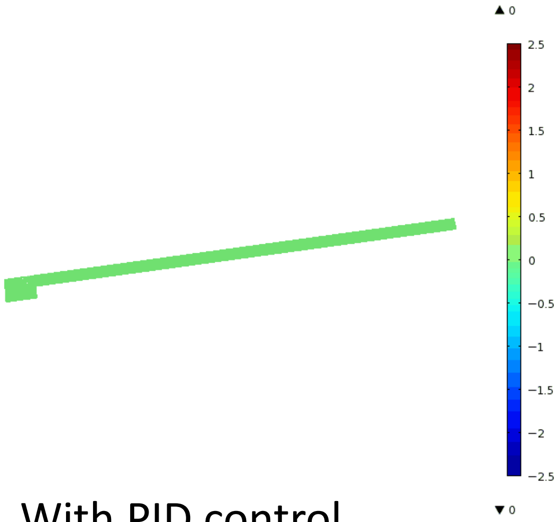


Validation

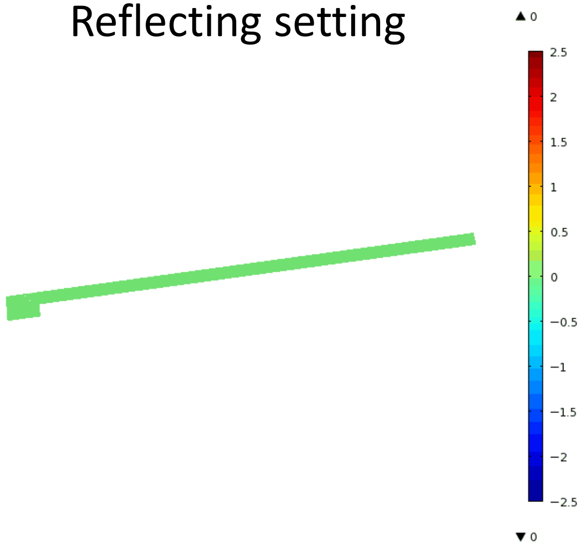
5. Validation vs. experiment



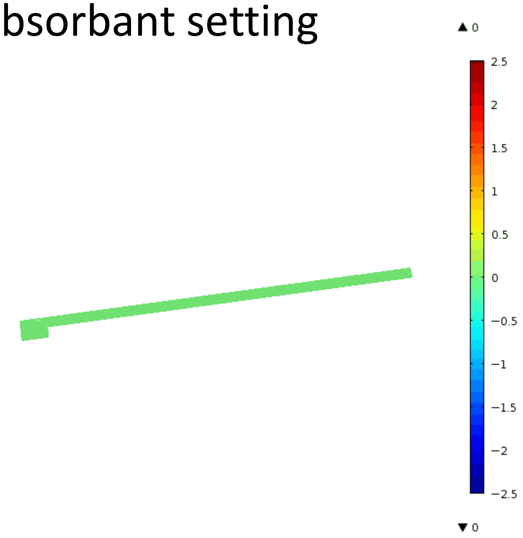
Without contrôle

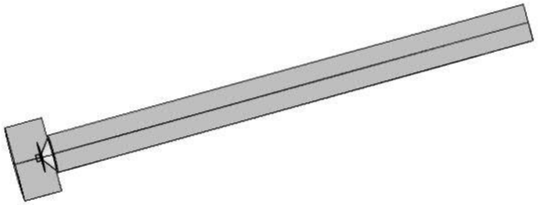


With PID control
Reflecting setting



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
  - ✓ Frequential 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 (frequential 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