H_∞ Multi-objective and Multi-Model MIMO control design for Broadband noise attenuation in a 3D enclosure

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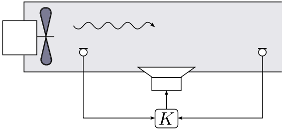
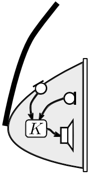


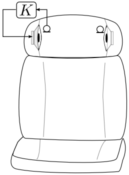
- Propagative waves
- Feedforward + feedback

Headphone



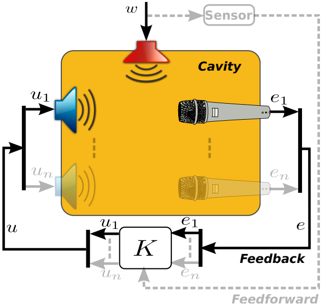
- SISO control
- Co-located actuator and sensor

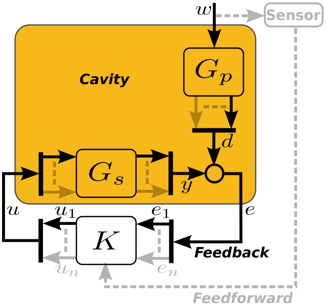
Headrest



- SISO control
- Co-located actuator and sensor

General Context
Active Noise Control (ANC) in a cavity



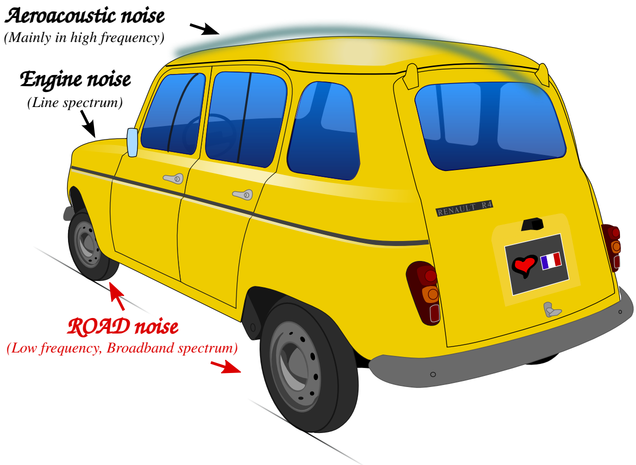


Characteristics of ANC in a cavity

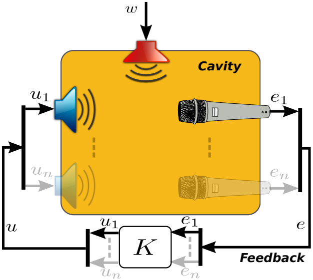
- Stationary waves
- Actuators and sensors co-located or not
- feedback or feedback + feedforward
- d narrow or broadband noise
- SISO or MIMO control

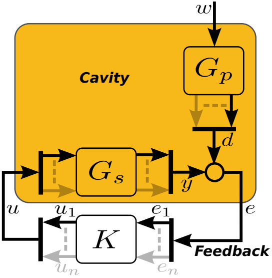
PhD objective

Active control of broadband low frequency noise in car cabin



- Passive treatments for low frequency noise $\Rightarrow$ Addition of weight
- Active Noise Control (ANC) is a great opportunity to simultaneously:
  - Reduce road noise
  - Achieve car weight reduction





ANC problem characteristics

- 3D enclosure
- Actuators and sensors not co-located
- No measure of *w* is available
- *d* broadband low frequency noise

Limitations involved

- Waterbed effect (Bode integral)
- Non minimum phase zeros

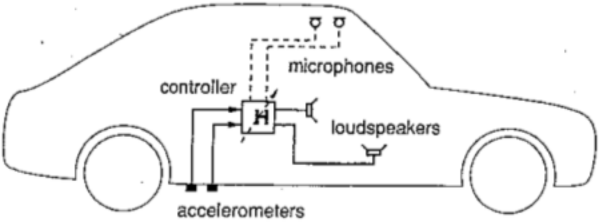


Fig. 2 – Control scheme for attenuation of interior noise in automobiles. Accelerometers attached to the bodywork provide reference signals for multiple-channel adaptive feedforward control. [1]

[1] T. Sutton, S. J. Elliott, M. McDonald, *et al.*, "Active control of road noise inside vehicles", *Noise Control Engineering Journal*, vol. 42, no. 4, pp. 137–147, 1994.

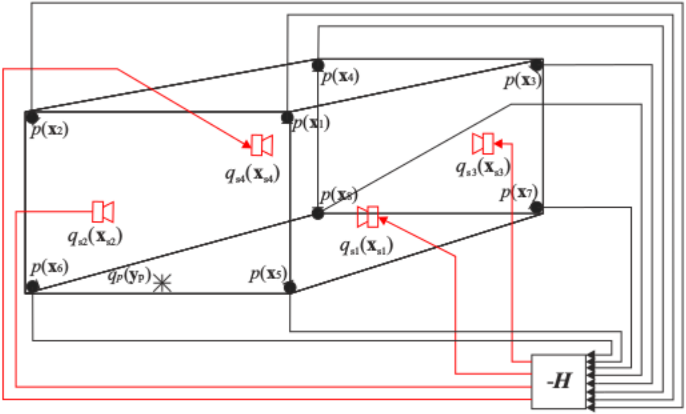
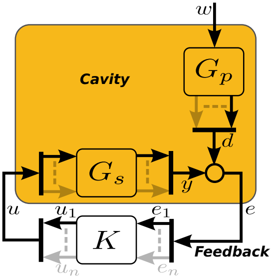


Figure 5.2: Mutli-input, multi-output feedback control system in the rectangular enclosure. [2]

[2] J. Cheer, “Active control of the acoustic environment in an automobile cabin”, PhD thesis, University of Southampton, Southampton, 2012, p. 346.

Scope of the presentation



Problem

- Attenuate broadband low frequency noise;
- In a closed cavity;
- by feedback.

Goal of the presentation

Compare SISO and MIMO achievable performances.

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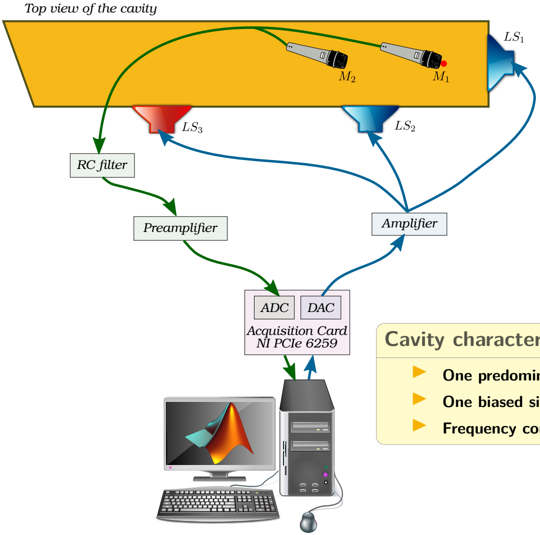
Experimental set up



Cavity characteristics

- **One predominant dimension:** 1D acoustic field in low frequency;
- **One biased side:** Attenuation of the first longitudinal mode;
- **Frequency complexity:** Similar to vehicle one.

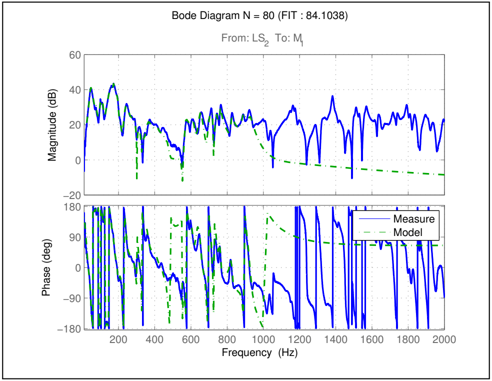
Identification

- **Algorithm:** Subspace;
- **Model structure:** Modal;
- **Frequency range:** [20-1000]Hz;
- **Order:** 80.

Fit indicator

	LS_1	LS_2	LS_3
M_1	86.2326	84.1038	91.1196
M_2	84.6231	88.8484	91.1542

Remark: SISO transfers contain RHP zeros.



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   - Multi-objective optimization
   - Controller Structure
   - Initialization
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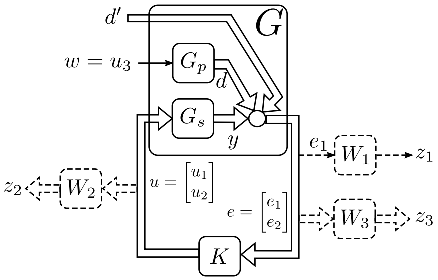
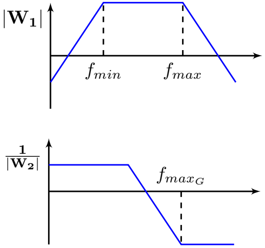
Control problem formulation

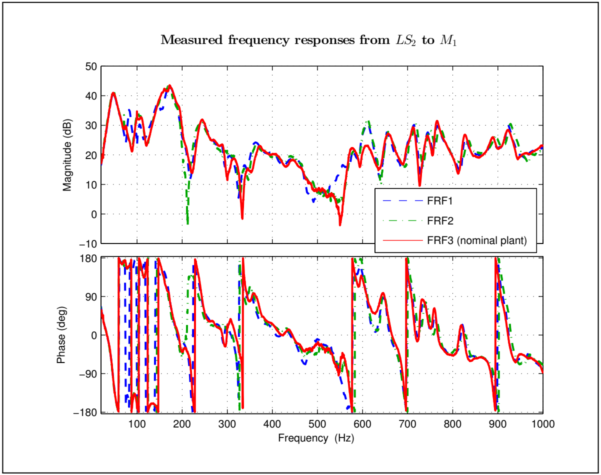




Optimization problem

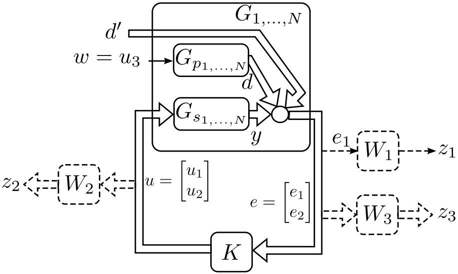
$$\min_{K} \left\| W_1 T_{w \to e_1} \right\|_\infty \quad \text{subject to} \quad \begin{cases} \left\| W_2 T_{w \to u_i} \right\|_\infty < 1 \\ \left\| W_3 T_{d'_j \to e_i} \right\|_\infty < 1 \\ |p_{i_K}| < f_e / N \\ Re(p_{i_K}) < 0 \end{cases} \quad i = 1, 2 \quad \text{and} \quad j = 1, 2$$

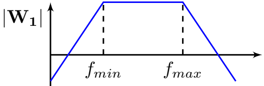
Environment conditions modify acoustic transfers

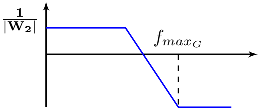


A **multi-model** approach was used to tackle system variations

Control problem formulation







Optimization problem

$$\min_{K} \max_{1,\ldots,N} \left\| W_1 T_{w \to e_1} \right\|_\infty \quad \text{subject to} \quad \begin{cases} \max_{1,\ldots,N} \left\| W_2 T_{w \to u_i} \right\|_\infty < 1 \\ \max_{1,\ldots,N} \left\| W_3 T_{d'_j \to e_i} \right\|_\infty < 1 \\ |p_{i_K}| < f_e / N \\ Re(p_{i_K}) < 0 \end{cases} \quad i = 1, 2 \quad \text{and} \quad j = 1, 2$$

Multi-objective and Multi-model optimization

Motivations

- Be able to consider various constraints **without pessimism**;
- Clearly distinguish objective and constraints;
- Have the possibility to mix H_2 and H_∞ objectives, if needed;
- Be able to structure the controller;
- Be able to consider reduce order controller.

Optimization tool: *systune*

- Specialized in tuning fixed-structure control systems;
- Based on non smooth optimization;
- P. Apkarian, "Tuning controllers against multiple design requirements", in *American Control Conference (ACC)*, Washington, 2013, pp. 3888–3893

Drawback

- May lead to local optima;
- Necessity of "good" initialization and controller structure.

Model of the system

- No real time measure of w
- G_p is known

$$\begin{cases} \dot{x} = Ax + B_u u + B_w w \\ e = Cx + D_u u + D_w w \end{cases}$$

Model of the controller

$$\begin{cases} \dot{\hat{x}} = A\hat{x} + B_u u + \mathbf{K_f}\left(e - \hat{e}\right) \\ u = -\mathbf{K_c}\hat{x} \end{cases}$$

Remarks

- K_f : observation gain
- K_c : state feedback gain
- full order controller

LQ criteria

$$J_{LQ} = \min_{K_c} \|W_{LQ}e\|_2^2 + \rho\|u\|_2^2$$

- W_{LQ} is a bandpass filter (attenuation frequency range)
- ρ manages trade-off between performances and control energy

Kalman filter

$$\begin{cases} \dot{x}_a = A_a x_a + B_{u_a} u + B_{w_a} w \\ e = C_a x_a + D_{u_a} u + D_{w_a} w + v \end{cases}$$

- Tuning parameters are the covariances of noises v and w

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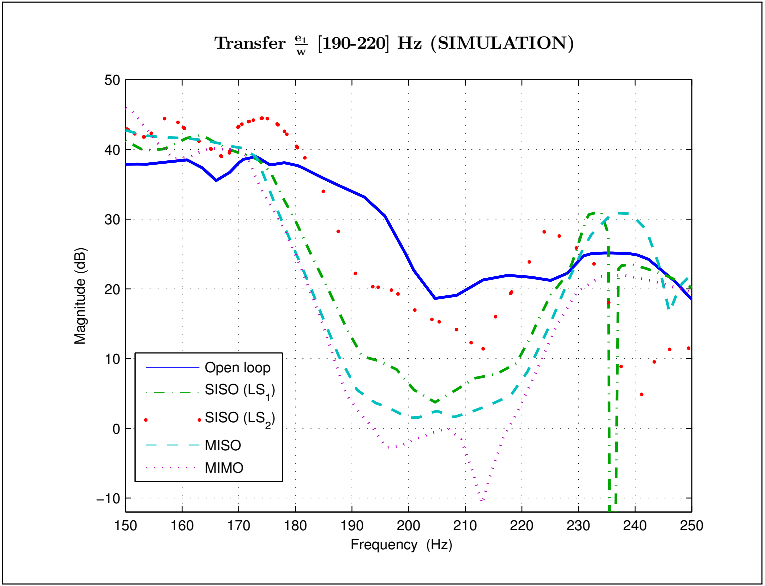
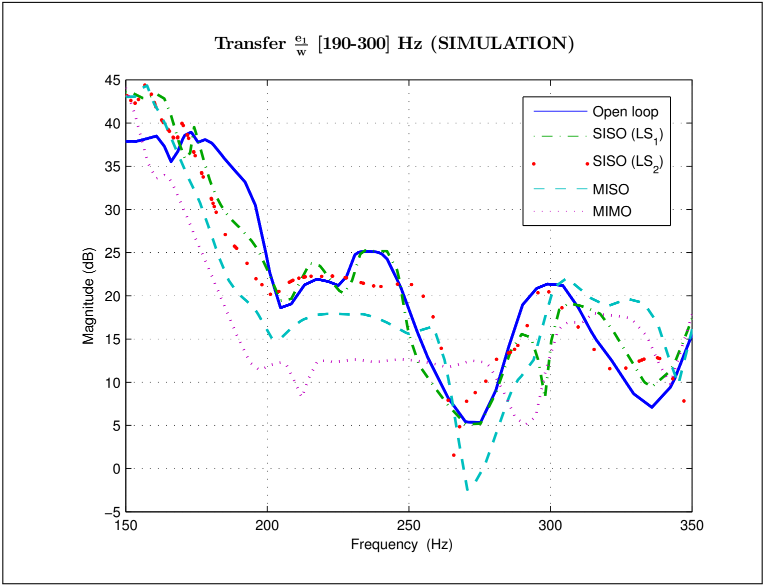
Results

Narrow attenuation: [190-220] Hz



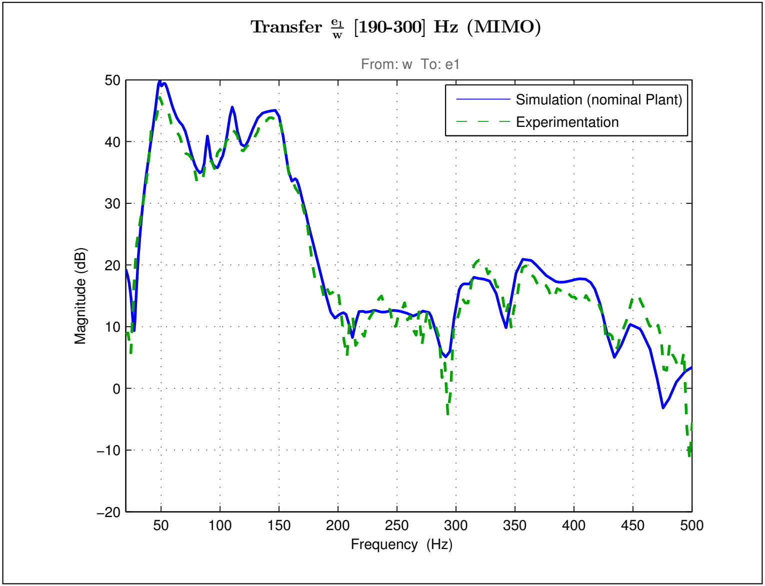
Results

Narrow attenuation: [190-300] Hz



Results

Experimentation: 190-300 Hz (MIMO)



Conclusions and Perspectives

Conclusions

- A general framework (for identification and control) was presented;
- It allows to quantify and compare SISO and MIMO achievable performances according to :
  - Frequency range of attenuation ;
  - Actuators and sensors position ;
  - Cavity geometry
  - ...

Ongoing work

- Compare feedback and feedforward control
- Apply methodology to the industrial problem where:
  - G_p is unknown
  - System order and dimensions are higher