A Nonlinear Piezoelectric Shunt Absorber with 2:1 Internal Resonance

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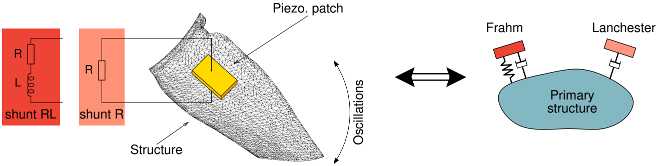
Piezoelectric shunts



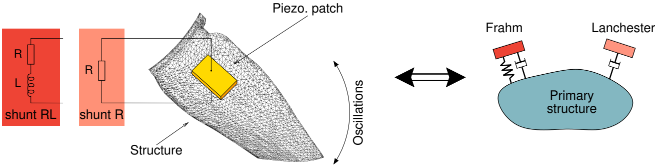
▷ Principle

- Piezoelectric patchs: mechanical / electrical energy conversion
- electric circuits:

  ⇝ mechanical energy dissipation,

  ⇝ counter vibrations.

Piezoelectric shunts



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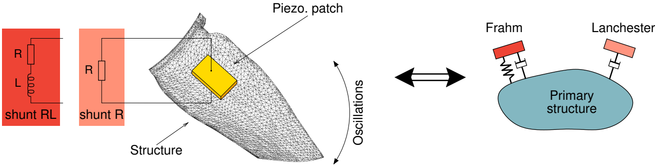
- Resistive shunt: the energy is dissipated in the electrical resistance
- Resonant shunt: electric equivalent of a tuned mass damper

Piezoelectric shunts



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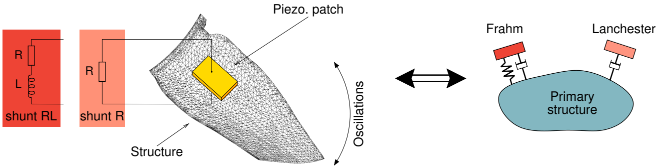
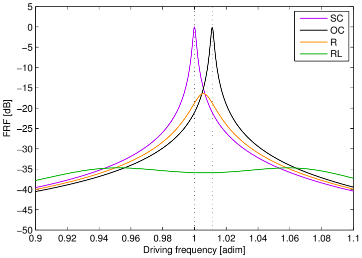
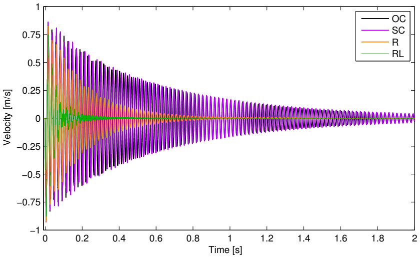
▷ **Passive devices**

- no external energy injected into the system (always stable)
- powered electronic components (semi-passive)

Resistive and resonant shunt responses





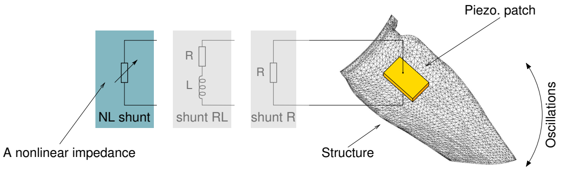


▷ **Resonant / resistive shunts** [Thomas *et al* SMS 2012]

Good performance, but fully linear...

⇝ **why not including nonlinearities in the shunt ?**

Today's talk and state of the art



▷ **Our work:**

- **including nonlinearities** in the shunt
- using **1:2 internal resonance for a saturation effect**

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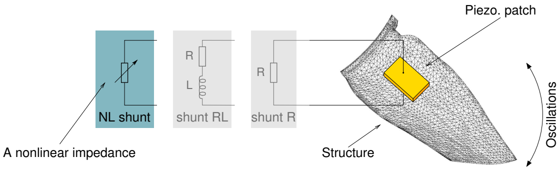

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- Some works using 1:2 internal resonance exist in active control [Nayfeh & Pai teams, 1996–]
- Our solution is a **semi-passive shunt**

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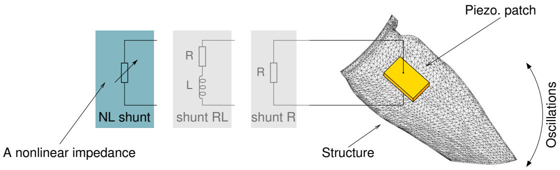

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▷ **Other families of works on piezoelectric nonlinear dampers:**

- Nonlinear Energy Sinks (NES) [Erturk team, SMS 2018], [Dekemele, Smart 2023]
- Nonlinear tuned vibration absorbers: a mirror of a primary nonlinear structure [Lossouarn, Raze, Kerschen, Deü 2018-]
- Synchronized Switch Damping [Guyomar team 2000-],. . .
- A non-smooth shunt (using a diode) [Shami, Thomas, Giraud-Audine, ND, 2023]

Two oscillators coupled in 1:2 internal resonance

$$\begin{cases} \ddot{x}_1 + 2\mu_1 \dot{x}_1 + \omega_1^2 x_1 + \alpha_1 x_1 x_2 = 0 & \leftarrow \text{secondary oscillator} \\ \ddot{x}_2 + 2\mu_2 \dot{x}_2 + \omega_2^2 x_2 + \alpha_2 x_1^2 = f_2 \cos \Omega t & \leftarrow \text{primary oscillator} \end{cases}$$

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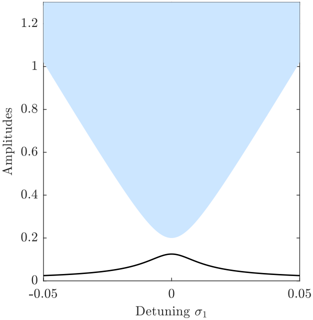

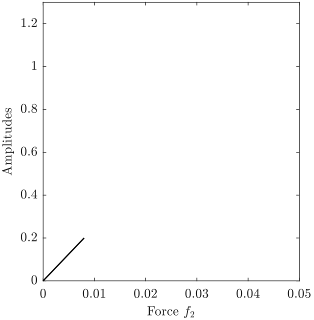

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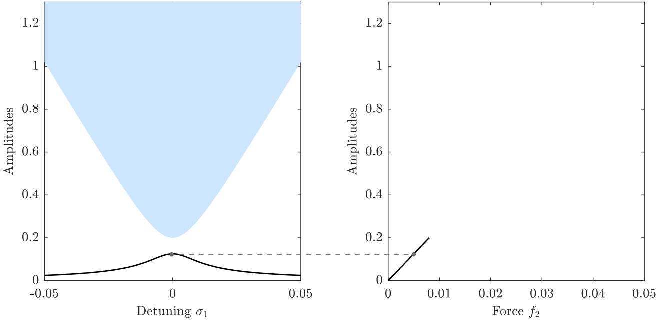

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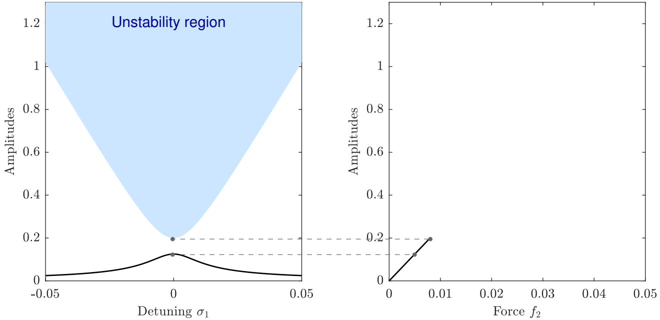

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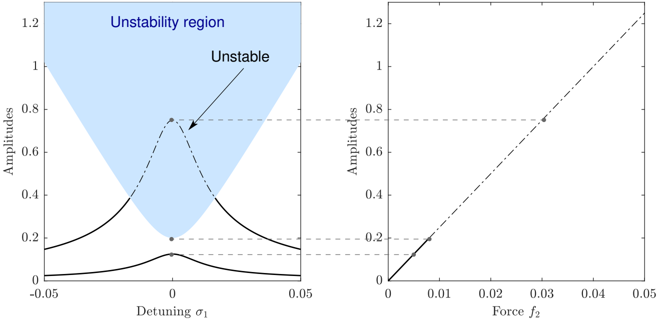

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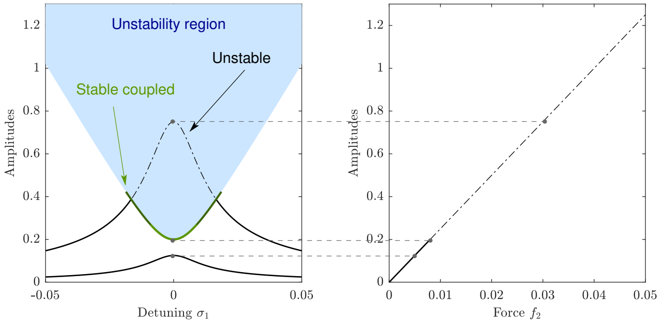

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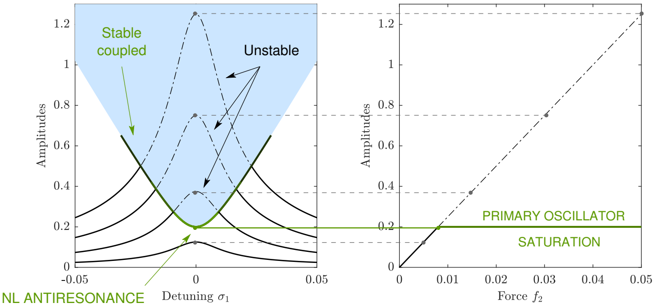

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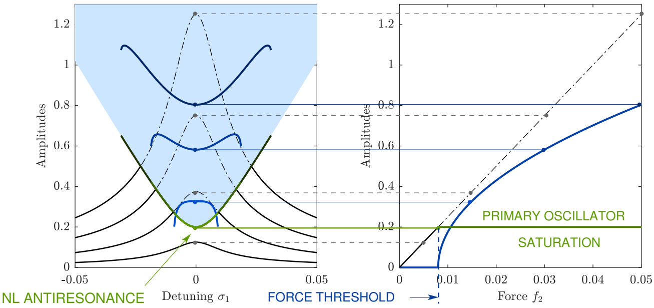

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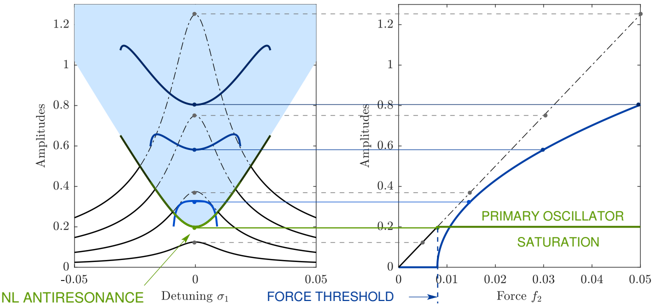
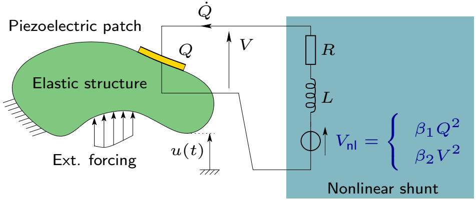


- Below the threshold $f_2 < f_2^*$: linear uncontroled response;
- **Above the threshold $f_2 > f_2^*$: nonlinear antiresonance + saturation of the amplitude** thanks to a subharmonic transfer of energy

Coupling a mechanical mode with an electrical circuit



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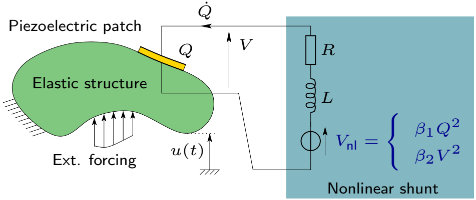

- One eigenmode expansion + piezoelectric coupling + resonant circuit:

$$\boldsymbol{u}(t) = \boldsymbol{\Phi}_i q_i(t) \quad \Rightarrow \quad \begin{cases} \ddot{q}_i + 2\xi_i \hat{\omega}_i \dot{q}_i + \hat{\omega}_i^2 q_i + \dfrac{\theta_i}{m_i C_{\text{p}i}} Q = \dfrac{F_i}{m_i} \cos \Omega t \\ \ddot{Q} + 2\xi_e \omega_e \dot{Q} + \omega_e^2 Q + \dfrac{\theta_i}{L C_{\text{p}i}} q_i + \dfrac{V_{nl}}{L} = 0 \end{cases}$$

$q_i(t)$ mechanical modal coordinate; $Q(t)$ electric charge; $(\hat{\omega}_i, \omega_e)$ mechanical and electrical natural frequencies: $\boxed{\omega_e = 1/\sqrt{LC} \simeq \hat{\omega}_i/2}$

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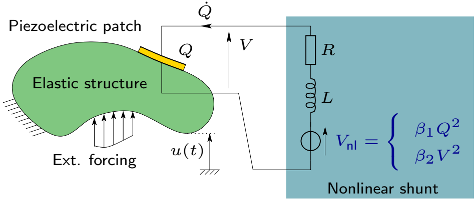

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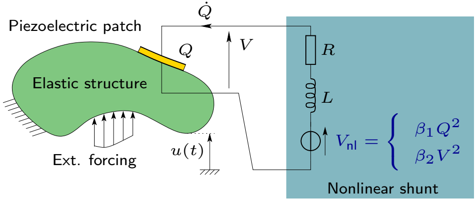

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- Linear piezoelectric coupling
- Nonlinear voltage source

  $\rightsquigarrow V_{nl} = \beta_1 Q^2 \Leftrightarrow$ a nonlinear capacitor (no simple passive component)

  $\rightsquigarrow V_{nl} = \beta_2 V^2$: easier in practice (see after).

Back to the canonical oscillators

- Expansion onto electromechanical modes $(\boldsymbol{\psi}_1, \boldsymbol{\psi}_2)$:

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with $q_i \simeq x_2$ ($\simeq$ mechanical mode) & $Q \simeq x_1$ ($\simeq$ electrical mode) because the piezoelectric coupling is often low.

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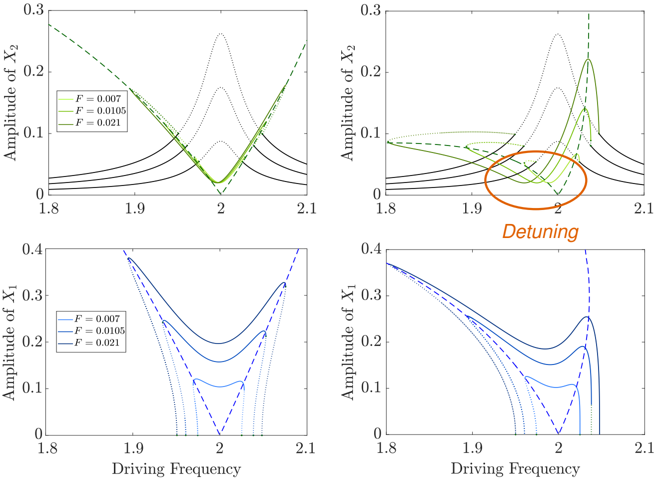
- If $\omega_2 \simeq 2\omega_1$, appearance of nonlinear quadratic:

⇝ resonant terms

⇝ but also non-resonant terms of large value (Λ_1 in particular).

the **non-resonant terms** are responsible of a **detuning of the nonlinear antiresonance** as a function of the amplitude of forcing

Effect of quadratic non resonant terms



Resonant terms only *All quadratic NL terms*

detuning of the nonlinear antiresonance $\Rightarrow$ loss of saturation of $x_2(t)$

Normal form transform & cubic terms

- From basic normal form theory, non-resonant quadratic terms are equivalent to cubic terms in the normal form:

$$\begin{cases} \ddot{x}_1 + \omega_1^2 x_1 + g_{11}^1 x_1^2 + g_{12}^1 x_1 x_2 + g_{22}^1 x_2^2 + \sum_{i,j,k} h_{ijk}^1 x_i x_j x_k = 0 \\ \ddot{x}_2 + \omega_2^2 x_2 + g_{11}^2 x_1^2 + g_{12}^2 x_1 x_2 + g_{22}^2 x_2^2 + \sum_{i,j,k} h_{ijk}^1 x_i x_j x_k = f_2 \cos \Omega t \end{cases}$$

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$$\Rightarrow \begin{cases} \ddot{r}_1 + \omega_1^2 r_1 + g_{12}^1 x_1 x_2 + \underbrace{(h_{111}^1 + A_{111}^1) r_1^3 + B_{111}^1 r_1 \dot{r}_1^2 + \dots}_{\text{cubic terms}} = 0 \\ \ddot{r}_2 + \omega_2^2 r_2 + g_{11}^2 x_1^2 + \underbrace{(h_{112}^2 + A_{111}^1 - D_{112}^2) r_1^2 r_2 + \dots}_{\text{cubic terms}} = f_2 \cos \Omega t \end{cases}$$

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- with **cubic terms** in the initial oscillators

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- From basic normal form theory, non-resonant quadratic terms are equivalent to cubic terms in the normal form:

$$\begin{cases} \ddot{x}_1 + \omega_1^2 x_1 + g_{11}^1 x_1^2 + g_{12}^1 x_1 x_2 + g_{22}^1 x_2^2 + \sum_{i,j,k} h_{ijk}^1 x_i x_j x_k = 0 \\ \ddot{x}_2 + \omega_2^2 x_2 + g_{11}^2 x_1^2 + g_{12}^2 x_1 x_2 + g_{22}^2 x_2^2 + \sum_{i,j,k} h_{ijk}^1 x_i x_j x_k = f_2 \cos \Omega t \end{cases}$$

$$\begin{pmatrix} x_p \\ \dot{x}_p \end{pmatrix} = \begin{pmatrix} r_p \\ \dot{r}_p \end{pmatrix} + \begin{pmatrix} \mathcal{P}_p^{(3)}(r_i, \dot{r}_i) \\ \mathcal{Q}_p^{(3)}(r_i, \dot{r}_i) \end{pmatrix}$$

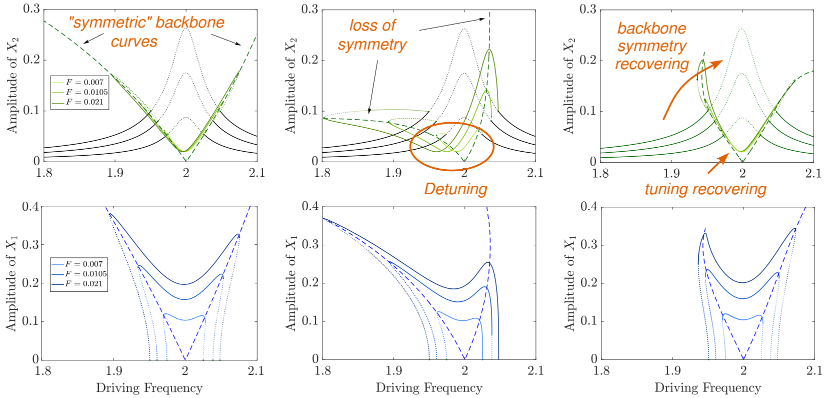
$$\Rightarrow \begin{cases} \ddot{r}_1 + \omega_1^2 r_1 + g_{12}^1 x_1 x_2 + \underbrace{(h_{111}^1 + A_{111}^1) r_1^3 + B_{111}^1 r_1 \dot{r}_1^2 + \dots}_{\text{cubic terms}} = 0 \\ \ddot{r}_2 + \omega_2^2 r_2 + g_{11}^2 x_1^2 + \underbrace{(h_{112}^2 + A_{111}^1 - D_{112}^2) r_1^2 r_2 + \dots}_{\text{cubic terms}} = f_2 \cos \Omega t \end{cases}$$

with A_{ijl}^k, B_{ijl}^k, D_{ijl}^k functions of quadratic **non-resonant** coefficients.

- with **cubic terms** in the initial oscillators

> Adding a **cubic term** in the shunt may help
> cancelling the effect of **quadratic non resonant** terms

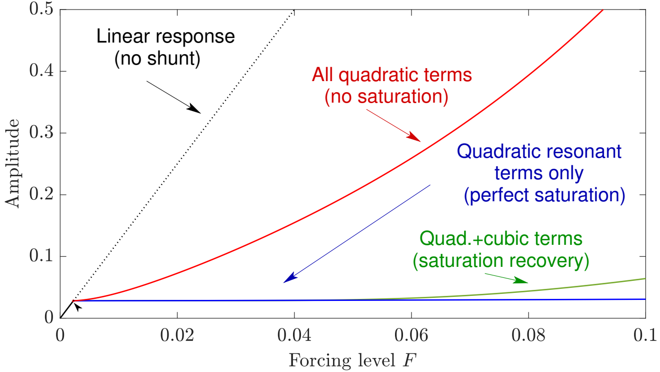
Annihilation of the effect of non-resonant terms



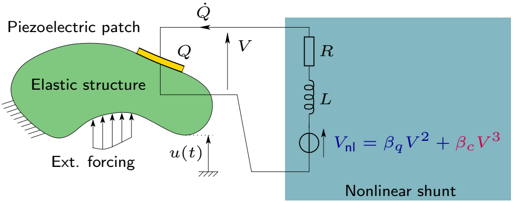
Resonant quadratic NL terms *All quadratic NL terms* *Quadratic + cubic terms*

We tune the cubic h^k_{ijl} terms to cancel the effect of the quadratic non-resonant terms on the **backbone curves** of the coupled 1:2 nonlinear modes: explicit formula $h^k_{ijl} = f(g^k_{ij})$.

Saturation recovery



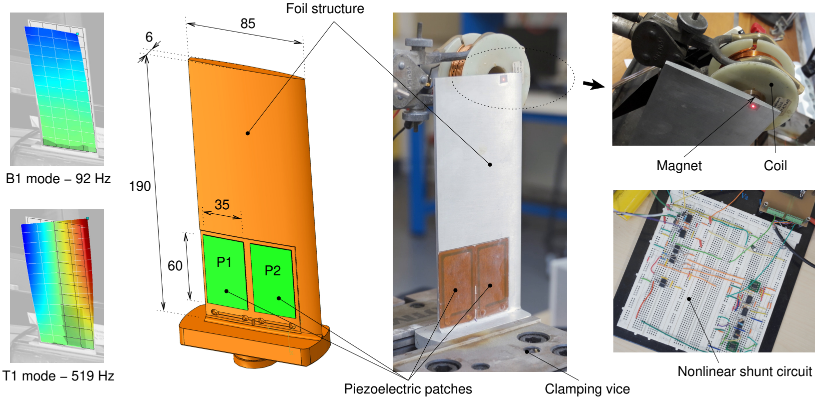
Quadratic & cubic shunt



- We add both quadratic and cubic NL terms in the shunt
- With only one degree of freedom (the alue of ceof. β_c), we are able to cancel only **the largest quadratic non resonant term (g_{11}^1)**, leading to:

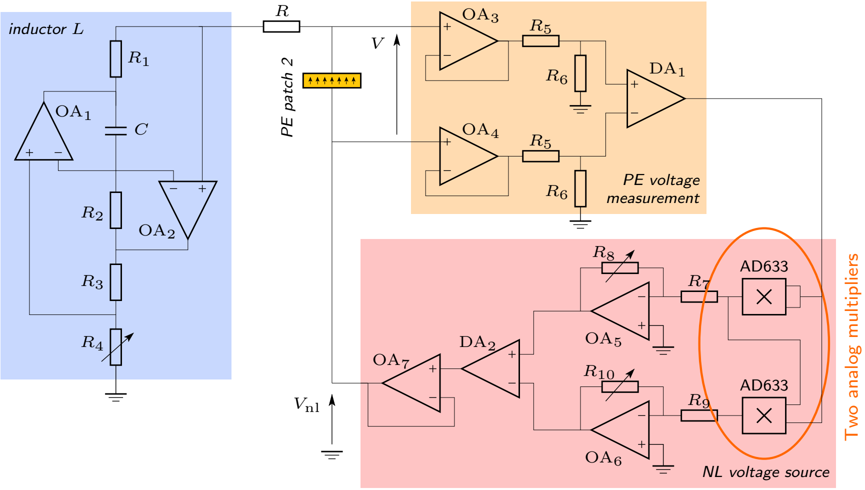
$$\boxed{\beta_c = \frac{10}{9}\beta_c^2}$$

Proof of concept on a hydroelastic foil model

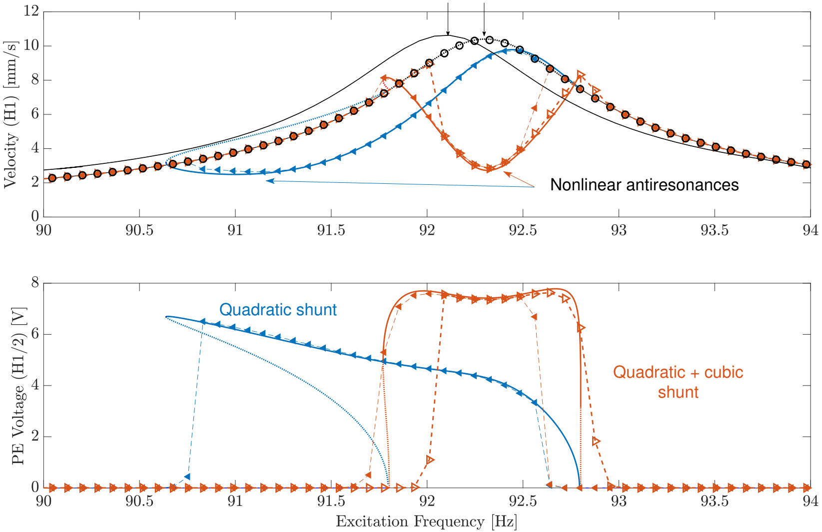


Nonlinear shunt tuned to damp the first bending mode ($92\ Hz$)

Analog electronic circuit with multipliers

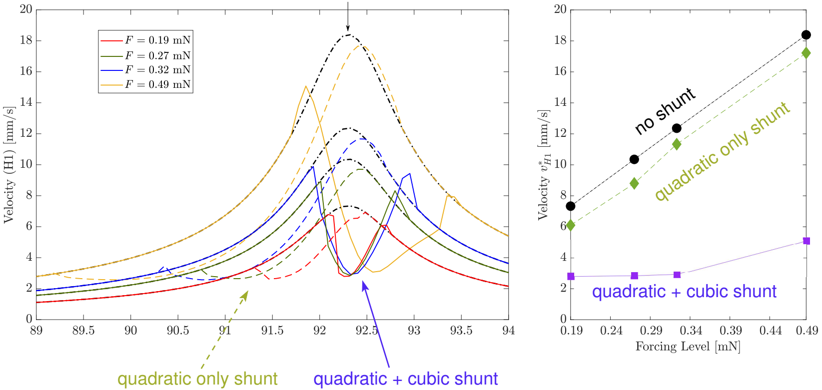


Experiments vs. theory



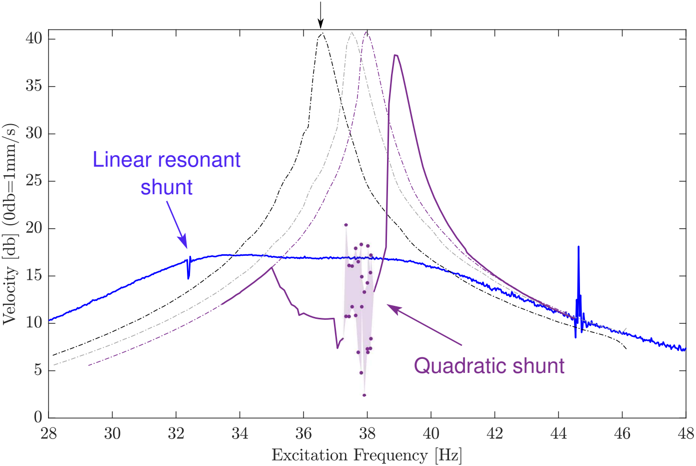
Perfect match !

Saturation effect



The cubic shunt clearly helps enhancing the saturation response range

Comparison to a linear resonant shunt



Because of the saturation, above a certain threshold (tunable) the nonlinear shunt **is better** than the linear resonant (RL) shunt.

Conclusions & perspectives

- The use of a 2:1 internal resonance with a **piezoelectric shunt** to obtain a control device based on **saturation** is fully demonstrated, theoretically & experimentally with analog electronic components;
- An unexpected effect of **non resonant** quadratic terms (*detuning* and *quasiperiodic responses*) was cancelled thanks to **cubic terms** & **normal form theory**;
- All optimization results are detailed in publications. Especially, the **figure of merit** of the shunt, for the saturation amplitude, is $\boxed{\xi_e/(\kappa\beta_q)}$ with ξ_e [-] electrical damping ratio, κ [-] piezoelectric coupling factor & β_c [V^{-1}] the quadratic voltage constant.

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- Z. A. Shami, C. Giraud-Audine, and O. Thomas. "A nonlinear piezoelectric shunt absorber with a 2:1 internal resonance : Theory" *Mechanical Systems and Signal Processing*, **170**:108768, 2022.
- Z. A. Shami, C. Giraud-Audine, and O. Thomas. "A nonlinear piezoelectric shunt absorber with 2:1 internal resonance: experimental proof of concept" *Smart Materials and Structures*, **31**:035006, 2022.
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THANK YOU !

Une annonce

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