9TH INTERNATIONAL WORKSHOP ON RELIABLE ENGINEERING COMPUTING
Risk and Uncertainty in Engineering Computations

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Hysteretic Tuned Mass Dampers for Seismic Protection

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May 20, 2021

Tuned Mass Damper

A **Tuned Mass Damper** (**TMD**) is a device that is attached to the main system in order to reduce the dynamic response that the latter exhibits when exposed to external excitations.

TMD Classification:

- Active
- Semi-active
- Hybrid
- **Passive**
    - **Conventional TMD**
    - Pendulum TMD
    - Tuned Liquid Damper

Taipei World Financial Center, Taiwan

Towards the seismic application

Despite the fact that TMDs are recognized as effective devices to mitigate wind-induced vibrations, their seismic effectiveness still remains an open issue.

Open challenges:

- **Detuning**

  (Wong KKF, Harris JL, 2012)
- **Impulsive loading**

  (Sladek, John R., and Richard E. Klingner, 1983)
- **Higher vibration modes**
- **Lack of experimentation**

LAX Theme Building

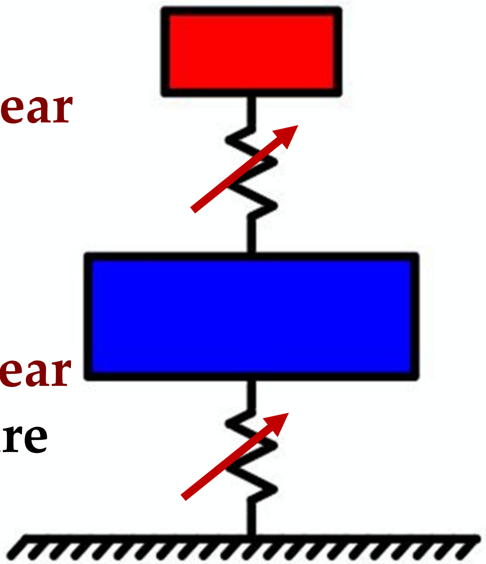
Berlin TV Tower

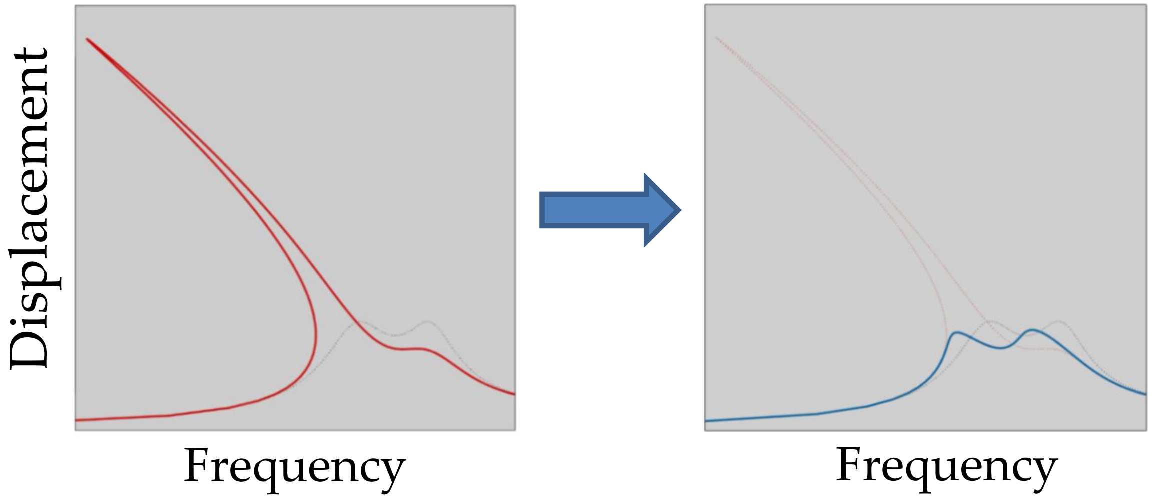
Detuning Effect

Nonlinear TMD

+

Nonlinear Structure





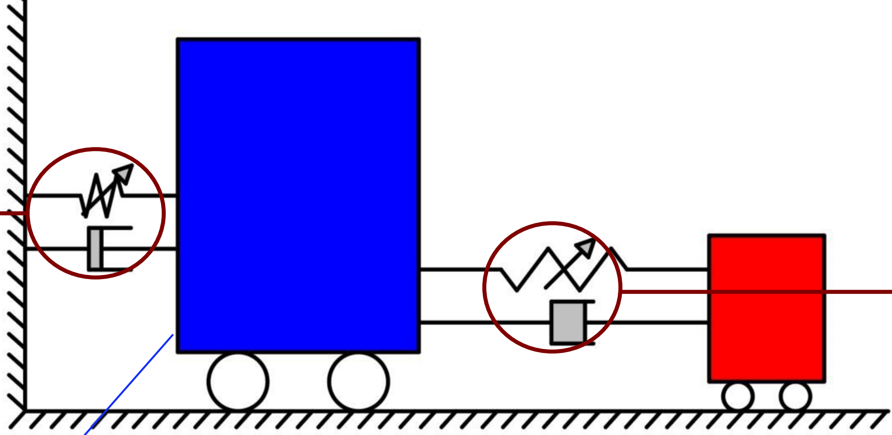
Innovative aspect of the work :

- taken into account, at the same time, the **nonlinear behaviour of the structures** to be controlled and the **nonlinear behaviour of the vibration absorber**;
- **new identification and optimization strategies** proposed.

Mechanical Model

2-DOFs System

Structure **TMD**

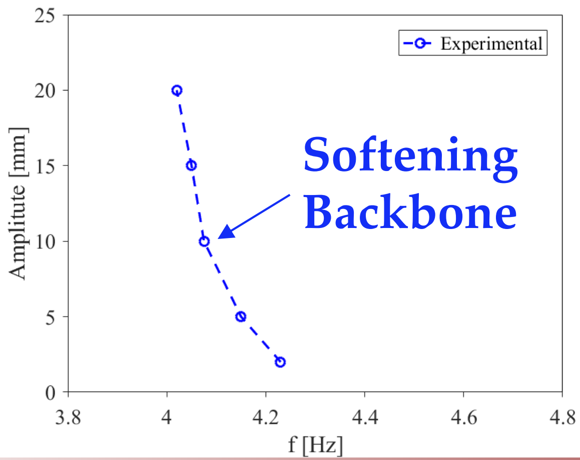


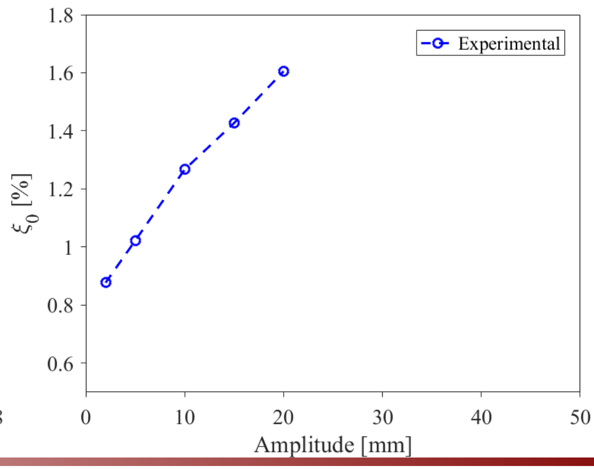
Bouc-Wen Model → **Identification**

Modified Bouc-Wen Model and Cubic stiffness → **Optimization**

$$\theta = \{k_{e_1},\ k_{d_1},\ \gamma_1,\ \beta_1,\ n_1\}$$

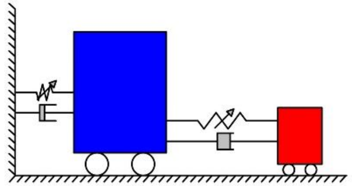
$$\mathbf{d} = \{k_{e2},\ k_{d2},\ \gamma_2,\ \beta_2,\ n_2,\ m_2,\ \xi_H,\ x_H\}$$





Carboni B. and W. Lacarbonara. *Journal of Engineering Mechanics* 142.5 (2016): 04016023.

The BW model of hysteresis



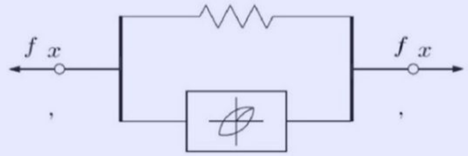
Structure: Bouc-Wen Model

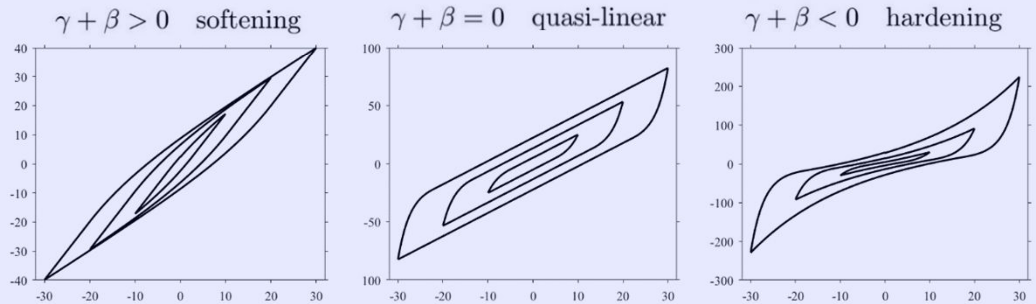
$$f(t) = k_e x + z$$

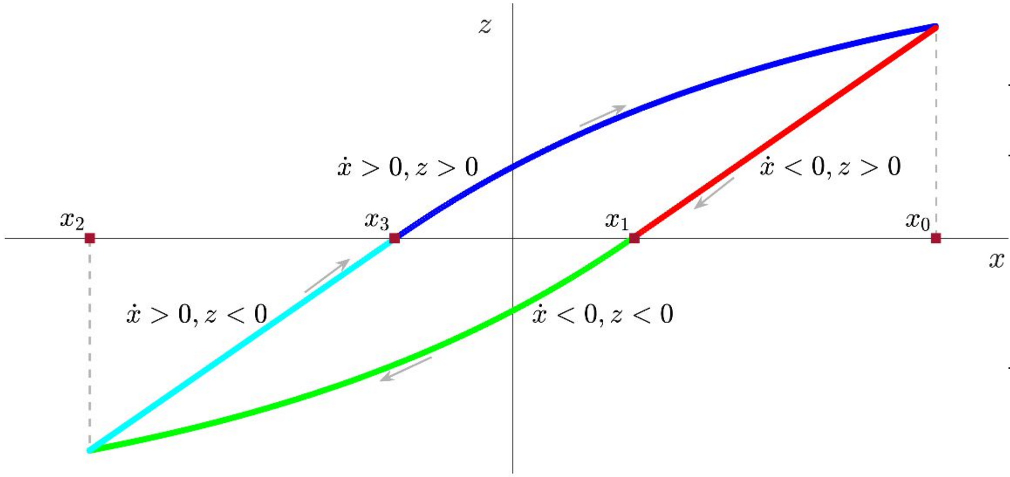
$$\dot{z} = \{k_d - [\gamma + \beta sgn(z\dot{x})]|z|^n\}\,\dot{x}$$

where $\gamma, \beta \in R$, $n \in R^+$

Softening/hardening behaviour — Smoothness transition

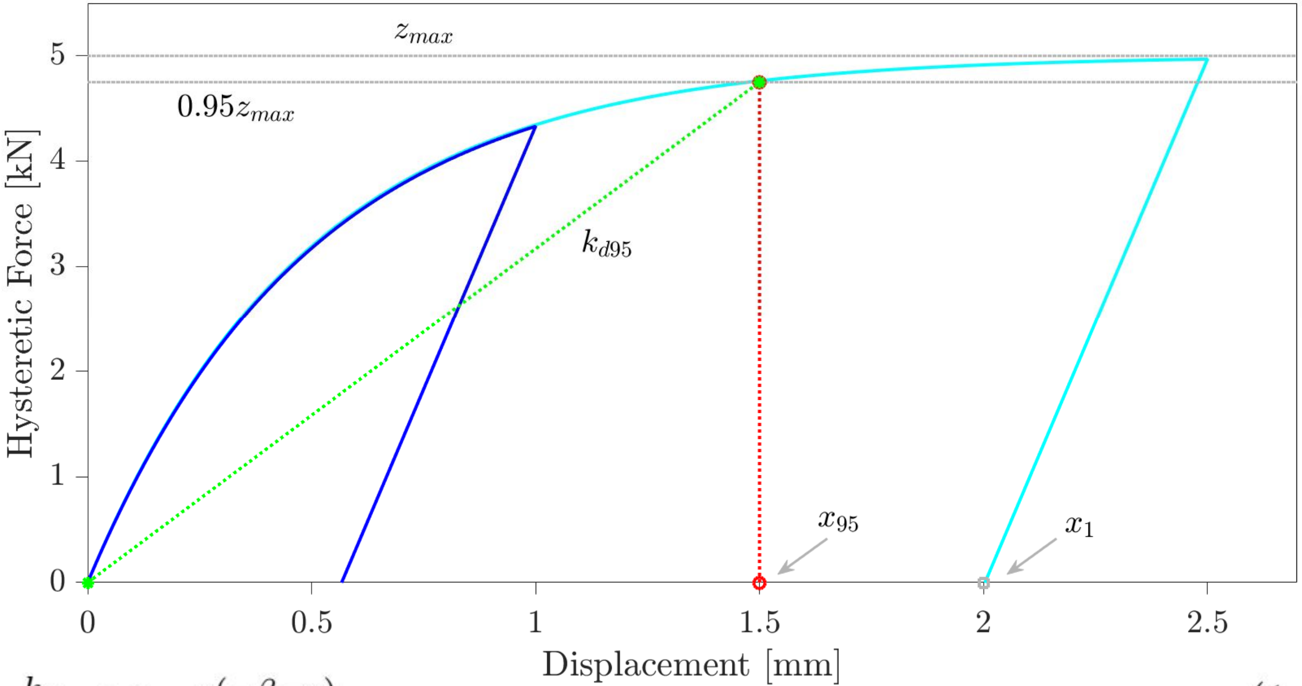






Branch	z	$\dot{x}$	z_x	z
1	>0	<0	$k_d + (\gamma - \beta)z$	$\frac{k_d}{\gamma-\beta} + b_1 e^{x(\beta-\gamma)}$
2	<0	<0	$k_d - (\gamma + \beta)z$	$-\frac{k_d}{\gamma+\beta} + b_2 e^{x(\beta+\gamma)}$
3	>0	<0	$k_d - (\gamma - \beta)z$	$\frac{k_d}{-\gamma+\beta} + b_3 e^{x(-\beta+\gamma)}$
4	>0	>0	$k_d + (\gamma + \beta)z$	$\frac{k_d}{\gamma+\beta} + b_4 e^{x(-\beta-\gamma)}$

The BW model of hysteresis



$z_{max} = -z_{min} = \frac{k_d}{\gamma + \beta}$

$$z_{fl}(x) = \frac{k_d}{\gamma+\beta} + b_4 e^{x(-\beta-\gamma)} \qquad \rightarrow \qquad b_4 = -\frac{k_d}{\gamma+\beta} \qquad \rightarrow \qquad z_{fl}(x) = \frac{(1-e^{-x(\gamma+\beta)})k_d}{\gamma+\beta}$$
$$z(0) = 0$$

$$z(x_{95}) = 0.95\, z_{max} \qquad \rightarrow \qquad x_{95} = \frac{-ln(0.05)}{\gamma+\beta} \simeq \frac{3}{\gamma+\beta}$$

$$k_{d95} = \frac{0.95\, z_{max}}{x_{95}} = \frac{0.95\, k_d}{-ln(0.05)} \simeq 0.317\, k_d$$

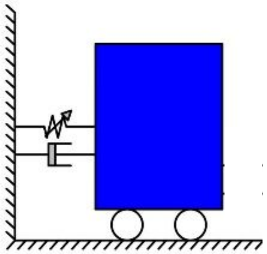
The hysteretic oscillator

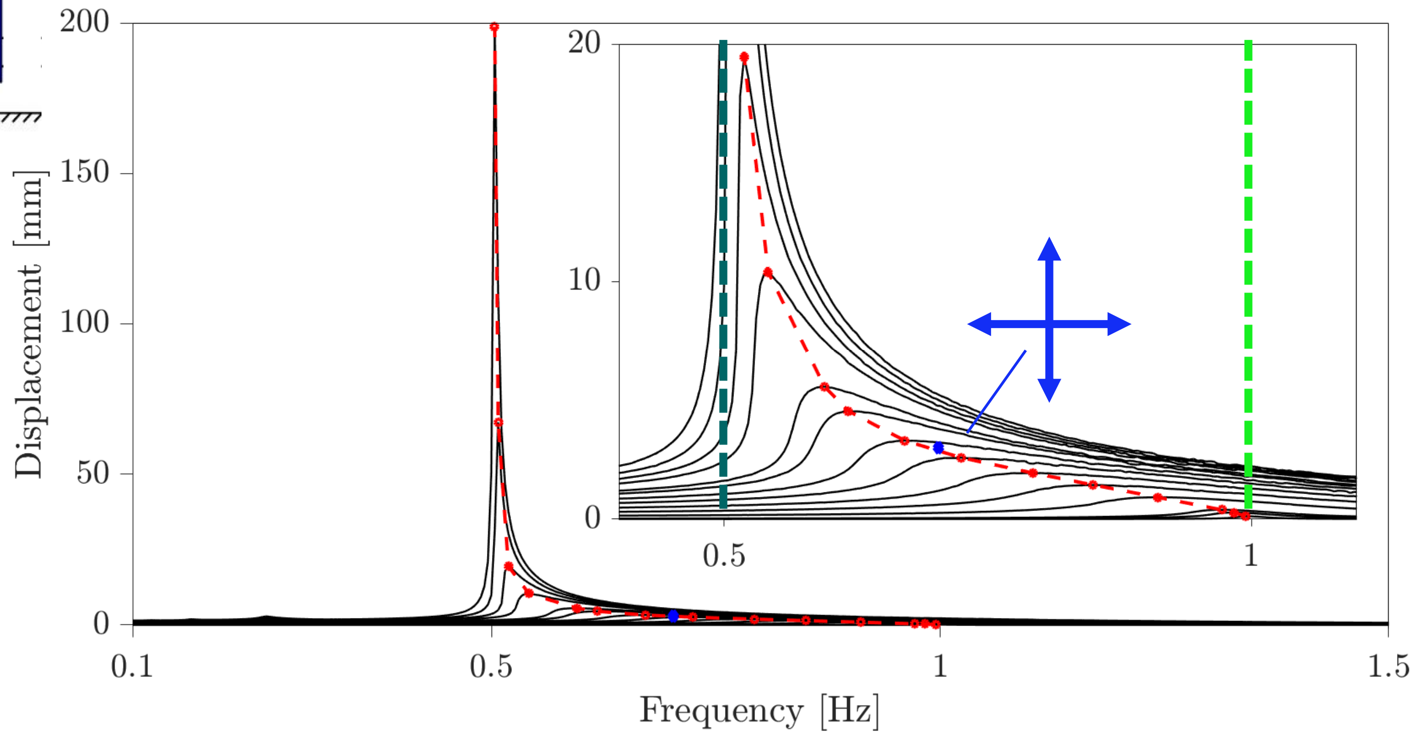
$$m\ddot{x} + f(x) = -m\ddot{x}_g$$
$$f(x) = k_e x + z(x)$$
$$\dot{z} = \{k_d - [\gamma + \beta\,\mathrm{sgn}(\dot{x}z)]|z|^n\}\dot{x}$$

$$m = 1\,\mathrm{kg}$$
$$k_e = 10\,\mathrm{N/m}$$
$$k_d = 30\,\mathrm{N/m}$$
$$\gamma = \beta = 0.5\,\mathrm{mm}^{-1}$$
$$n = 1$$

$$f_{ul} = \frac{1}{2\pi}\sqrt{\frac{k_e}{m}} = 1.00\,\mathrm{Hz}$$
$$f_{in} = \frac{1}{2\pi}\sqrt{\frac{k_e+k_d}{m}} = 0.50\,\mathrm{Hz}$$

$$f_{95} = \frac{1}{2\pi}\sqrt{\frac{k_e+0.317k_d}{m}} = 0.70\,\mathrm{Hz}$$
$$x_{95} = \frac{3}{\gamma+\beta} = 3.00\,\mathrm{mm}$$





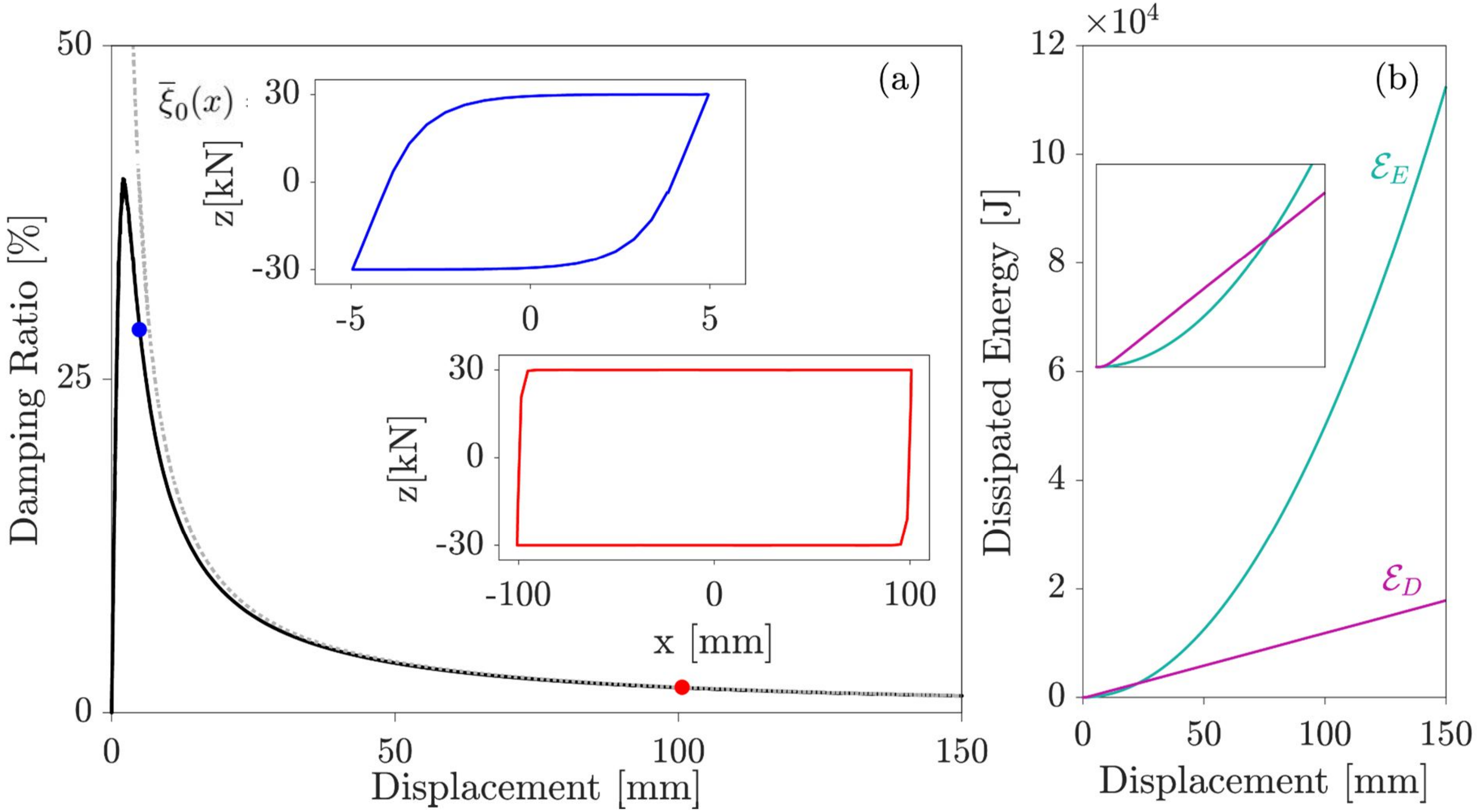
The hysteretic oscillator

$$\xi_0 = \frac{\mathcal{E}_D}{4\pi\,\mathcal{E}_E}$$

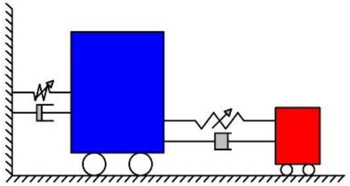
$$\mathcal{E}_E = \frac{1}{2}\,k_e\,x_0^2$$

$$\mathcal{E}_D = \int_{-x_0}^{x_0} z\,dx \simeq 4\,z_{max}\,x_0$$

$$\bar{\xi}_0(x) = \frac{2\,k_d}{k_e\pi(\gamma+\beta)\,x}$$



The modified BW model of hysteresis



TMD: Modified Bouc-Wen Model

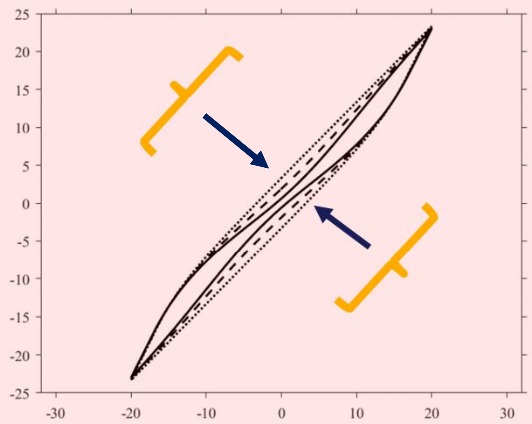
$$\dot{z} = \{k_d H(x) - [\gamma + \beta sgn(z\dot{x})]|z|^n\}\,\dot{x}$$

$$H(x) = 1 - \xi_0 e^{\frac{x^2}{x_0}}$$

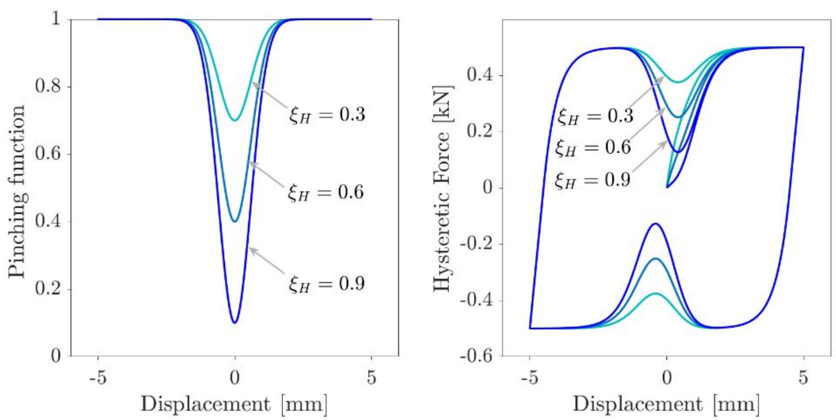
Pinching function

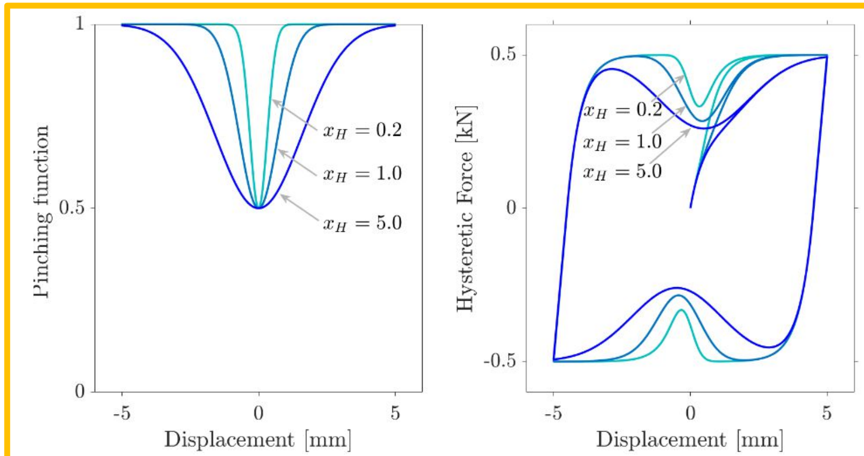
where $x_0 \in R^+$, $\xi_0 \in [0,1)$

Extension — Intensity

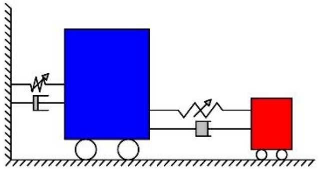


Biagio Carboni, Walter Lacarbonara, and Ferdinando Auricchio. *Journal of Engineering Mechanics* 141.3 (2014): 04014135.





Nonlinear Structural Identification



- Structural parameters to be identified: $\theta = \{k_{e_1}, \quad k_{d_1}, \quad \gamma_1, \quad \beta_1, \quad \cancel{n_1}\}$

  $(n = 1)$

- Analytical Optimization

$$\begin{aligned}
\overline{f}_{ul} &= \tfrac{1}{2}\sqrt{\tfrac{\overline{k}_{e1}}{m_1}} = 4.23\,\text{Hz} \rightarrow \overline{k}_{e1} = 0.3610\,\text{kN/mm} \\
\overline{f}_{in} &= \tfrac{1}{2}\sqrt{\tfrac{\overline{k}_{e1}+\overline{k}_{d1}}{m_1}} = 4.02\,\text{Hz} \rightarrow \overline{k}_{d1} = 0.0387\,\text{kN/mm} \\
\overline{f}_{95} &= \tfrac{1}{2}\sqrt{\tfrac{\overline{k}_{e1}+0.317\,\overline{k}_{ed}}{m_1}} = 4.0875\,\text{Hz} \rightarrow \overline{x}_{95} \cong 10\,\text{mm} \\
\overline{x}_{95} &= \tfrac{3}{\overline{\gamma}_1+\overline{\beta}_1} \rightarrow \overline{\gamma}_1 + \overline{\beta}_1 = 0.30\,\text{mm}^{-1}
\end{aligned}$$

- Numerical Optimization: **Differential Evolution Alghoritms**

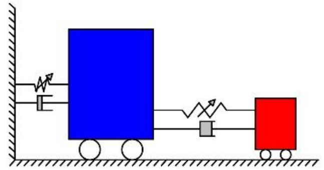
R Storn and K Price, *Journal of global optimization*, vol. 11, no. 4, pp. 341–359, 1997.

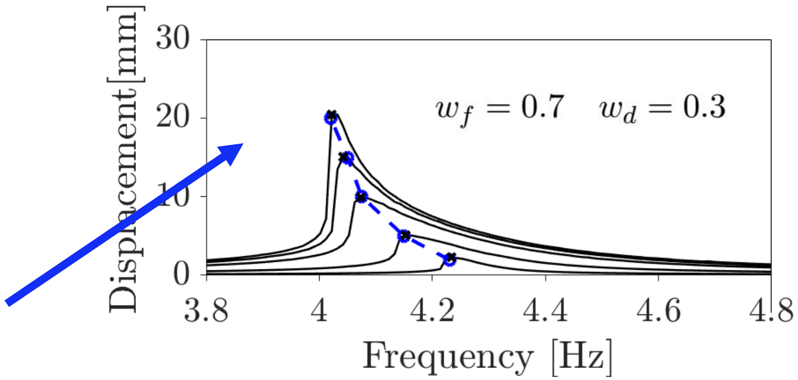
Cost function:

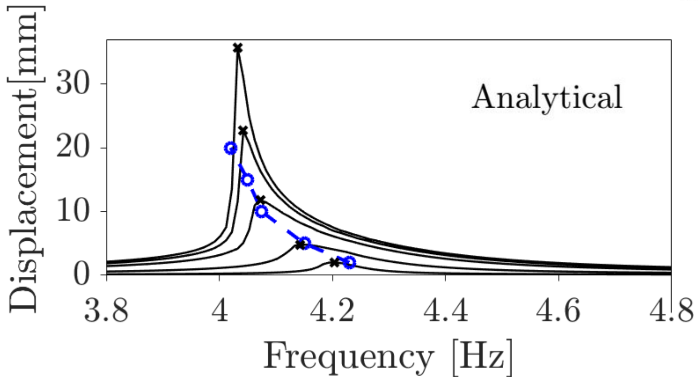
$$\Phi_{id}(\boldsymbol{\theta}) = \sum_{i=1}^{M} w_f \frac{(f_{ex,i} - f_{m,i}(\boldsymbol{\theta}))}{f_{ex,i}} + w_\xi \frac{(\xi_{ex,i} - \xi_{m,i}(\boldsymbol{\theta}))}{\xi_{ex,i}}$$

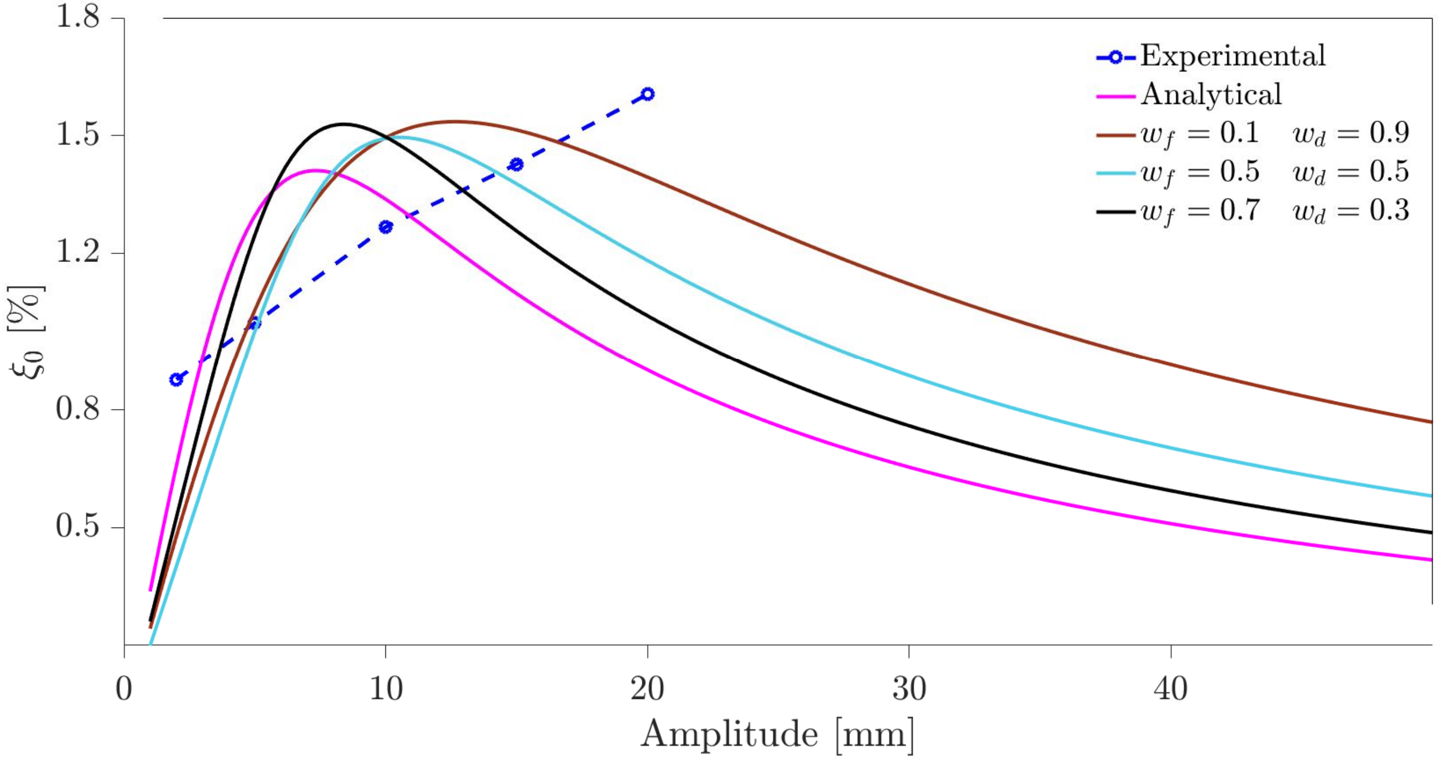
Resonant frequency		**Damping**		**Weight function**	
f_{ex}	Experimental	ξ_{ex}	Experimental	w_f	Frequency
f_m	Estimated frequency	ξ_m	Estimated	w_ξ	Damping

Nonlinear Structural Identification

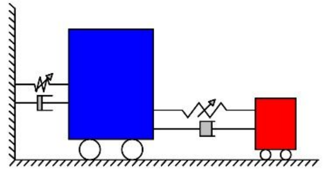








Optimum design of the hysteretic TMD



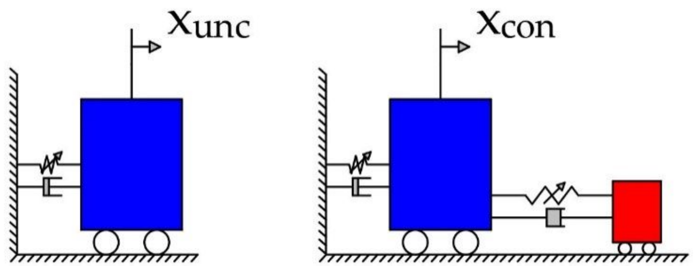
- TMD parameters to be optimized: $\mathbf{d} = \{k_{e2},\ k_{d2},\ k_{c2},\ \gamma_2,\ \beta_2,\ n_2,\ m_2,\ \xi_H,\ x_H\}$
- Optimization method: **Differential Evolution Alghoritms**

$n_2 = 1$

$\mu = \frac{m_2}{m_1} = \{1\%,\ 2\%,\ 5\%\}$

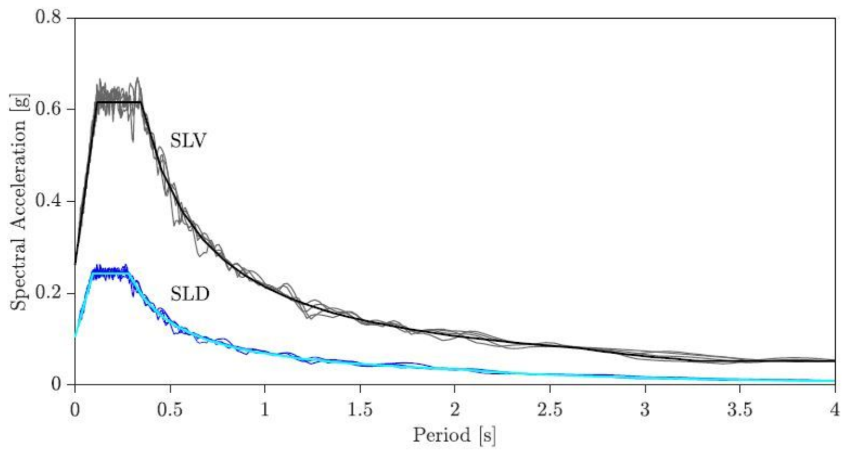
Cost function:

$$R_t(\mathbf{d}) = 1 - \Psi_t(\mathbf{d})$$



Input

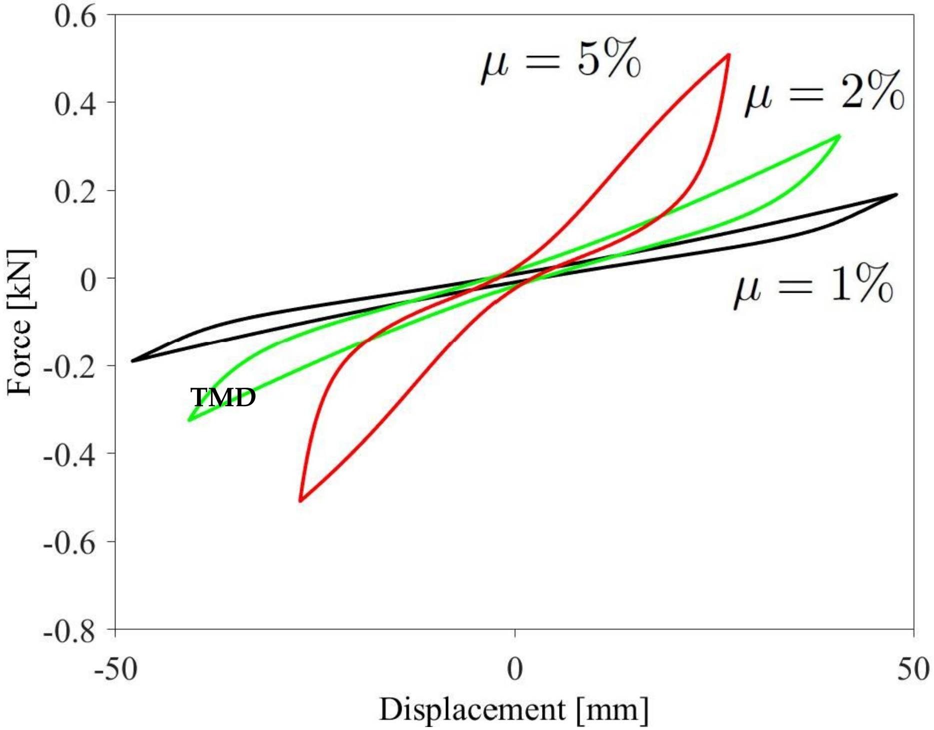
4 SLD + 4 SLV



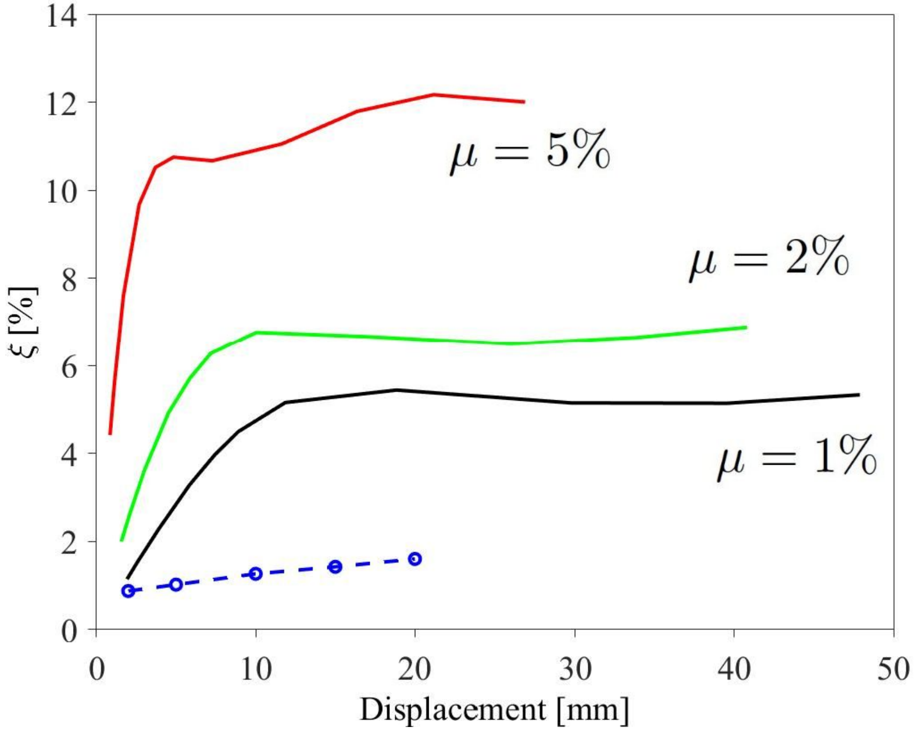
k_{d_2} $\left[\frac{kN}{mm}\right]$	k_{c2} $\left[\frac{kN}{mm^3}\right]$	γ_2 $\left[\frac{kN^{1-n_1}}{mm}\right]$	β_2 $\left[\frac{kN^{1-n_1}}{mm}\right]$	ξ_H $[-]$	x_H $[mm^2]$
$\frac{k_{e_1}}{1000}$	0	$\frac{\gamma_1}{1000}$	$\frac{\beta_1}{1000}$	0	20
$30k_{e_1}$	k_{e1}	$100\gamma_1$	$100\beta_1$	0.985	40000

Optimized hysteretic TMD

Force-Displacement Cycles

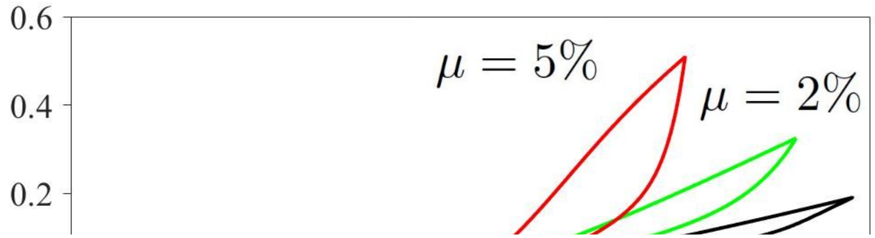


Dampings

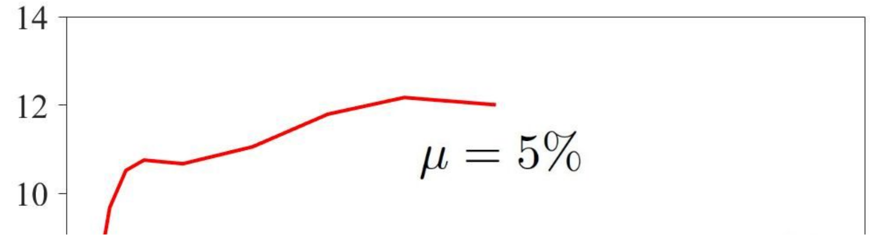


Optimized hysteretic TMD

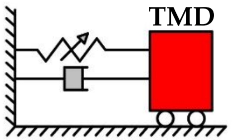
Force-Displacement Cycles

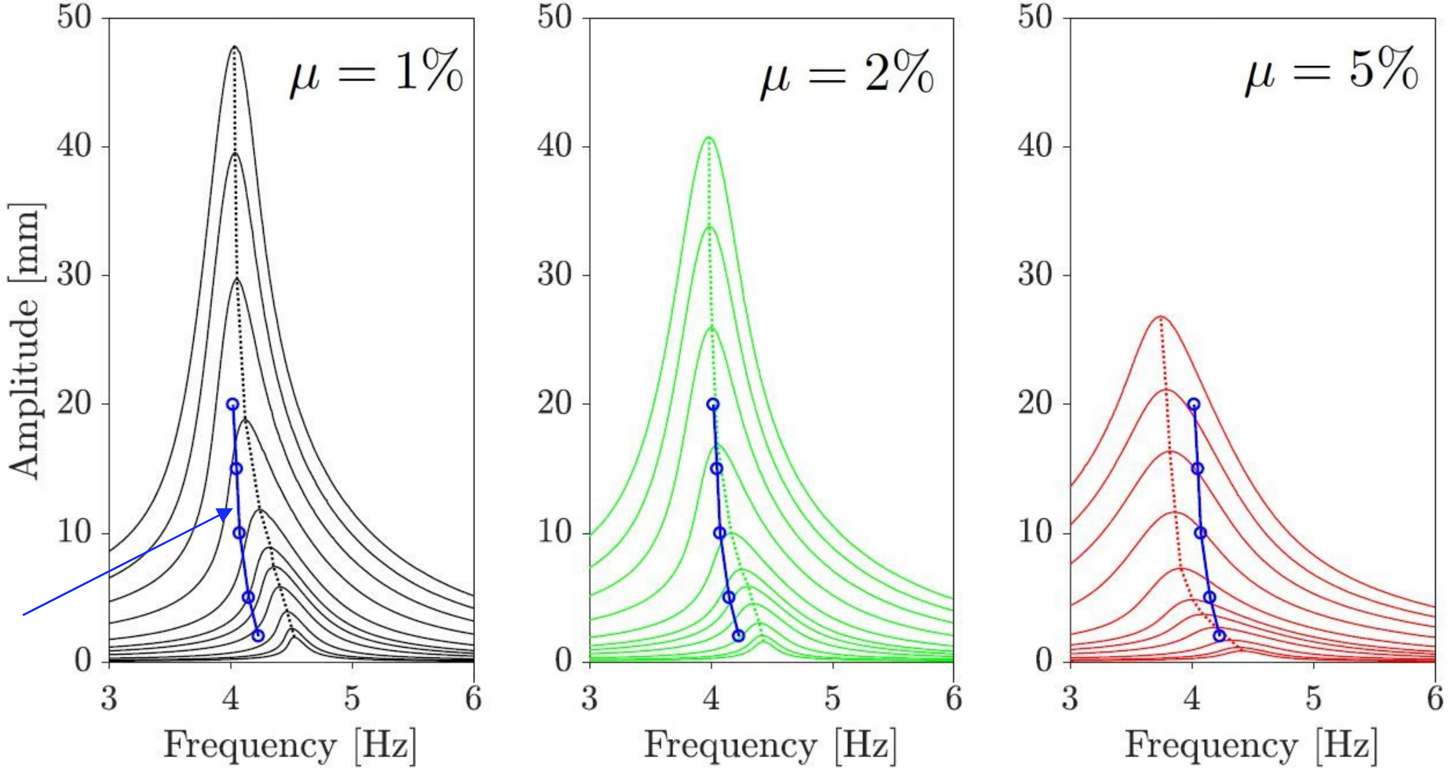


Dampings



FRCs 1DOF

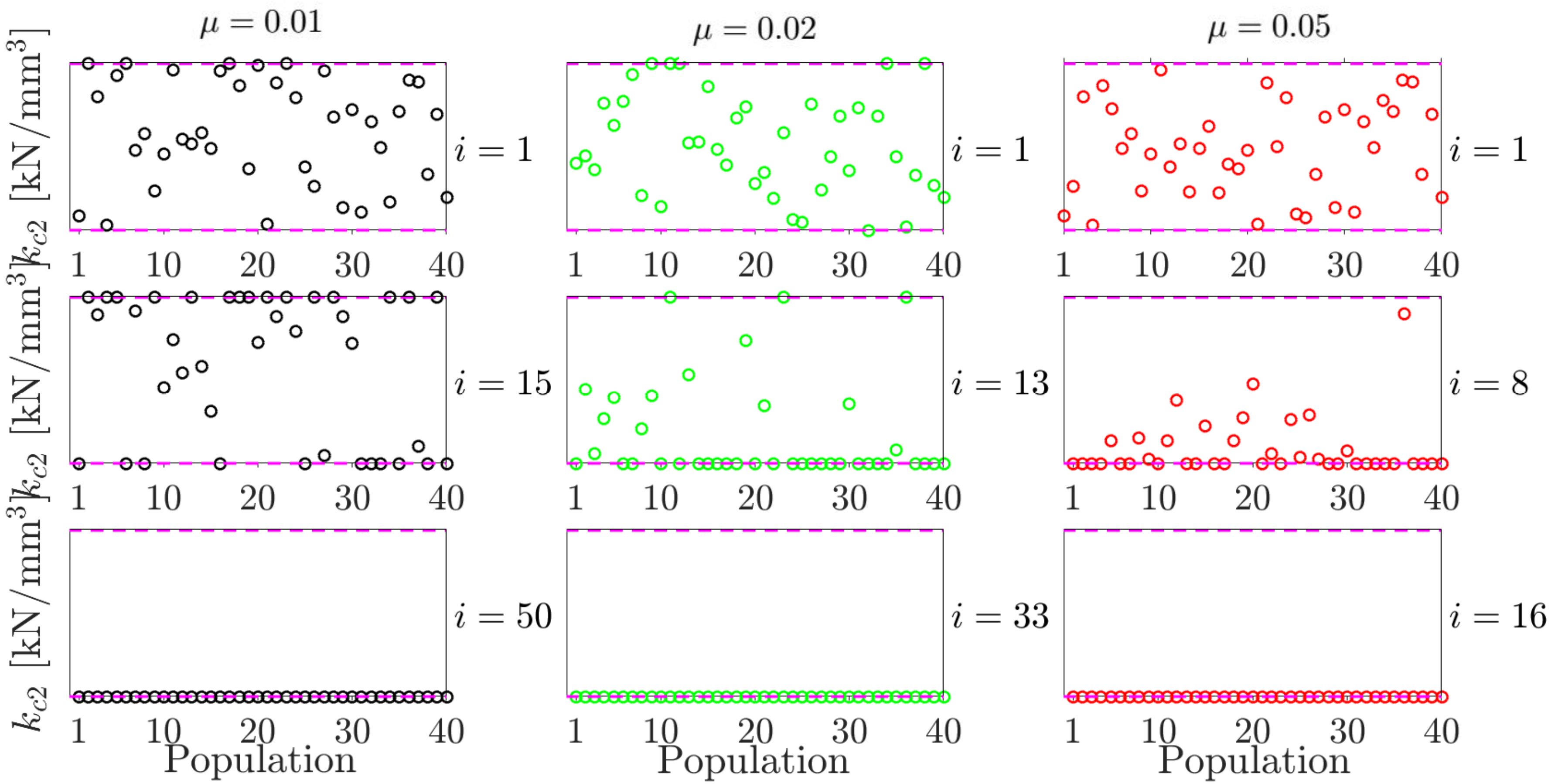




Experimental structural Backbone

Optimized hysteretic TMD

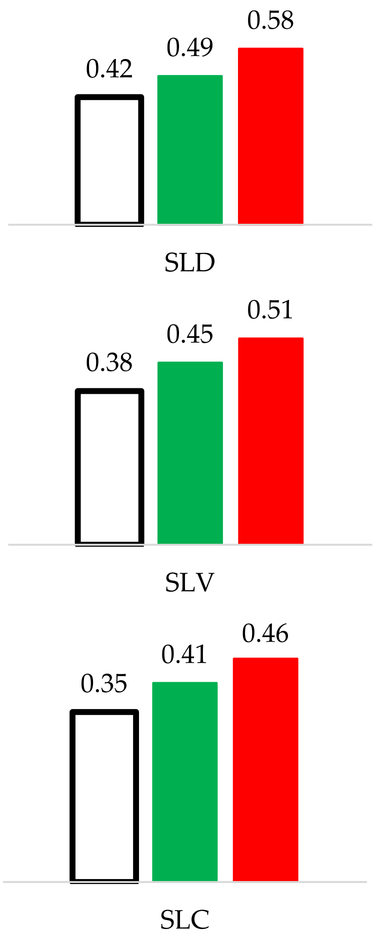
Effect of the cubic elastic stiffness



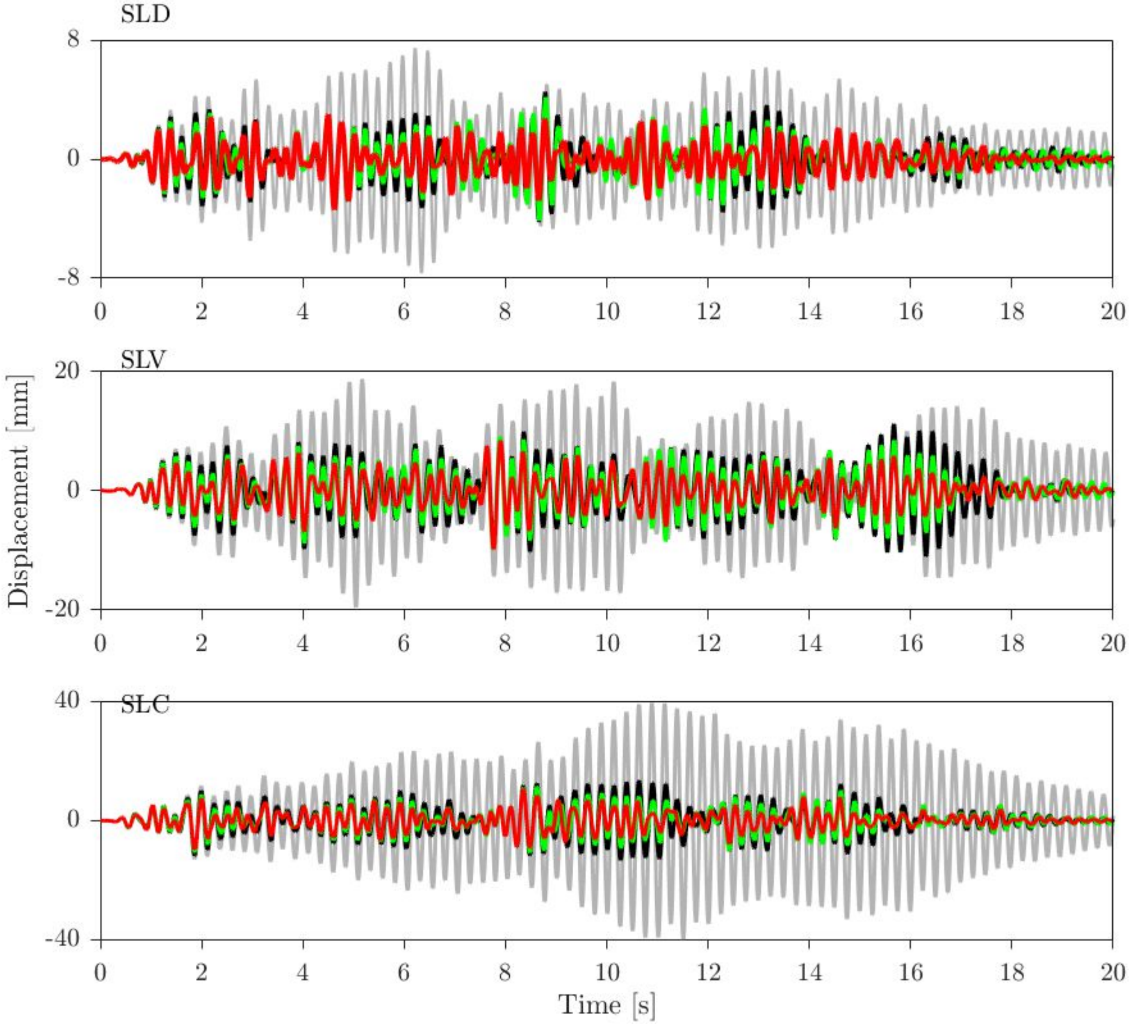
Not needed!

Optimized hysteretic TMD: mitigation capability

Objective function Rt for each limit state



Displacement reductions



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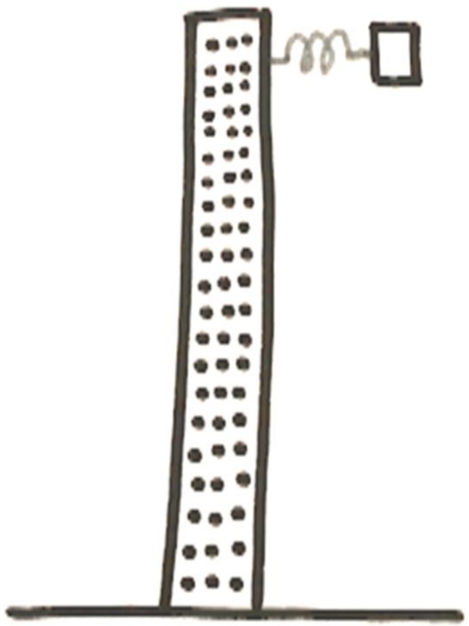
Conclusions

Main achievements:

- ✓ Novel **identification** technique for nonlinear structures and **optimization** of TMD parameters based on **Differential Evolution** are proposed.
- ✓ **Design formulas** were obtained in order to identify the hysteretic **structures**.
- ✓ Improvement in the RMS displacement mitigation: over **40%** for **steel-made** structures, were obtained using hysteretic TMD endowed with a mass corresponding to **1%** of the mass of the structure.
- ✓ The optimized force-displacement cycles showed a **pronounced pinching shape**.
- ✓ The pinched hysteretic TMD is effective in protecting a nonlinear hysteretic structure thanks to its **softening-type backbone**, which can be optimized to **accommodate the frequency changes** that the engineering structures undergo when subject to seismic events.



Thank you for your attention

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