SAPIENZA
UNIVERSITÀ DI ROMA

Shape-memory alloys and applications in vibration mitigation

Unità locale La Sapienza:

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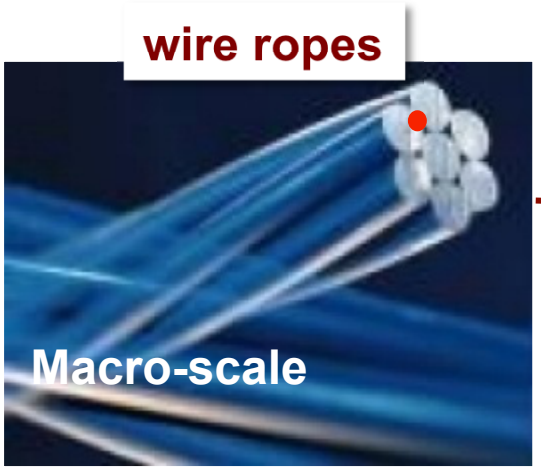
Dipartimento di Ingegneria Strutturale e Geotecnica

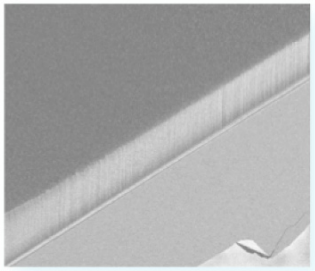
Kick-Off PRIN 2008

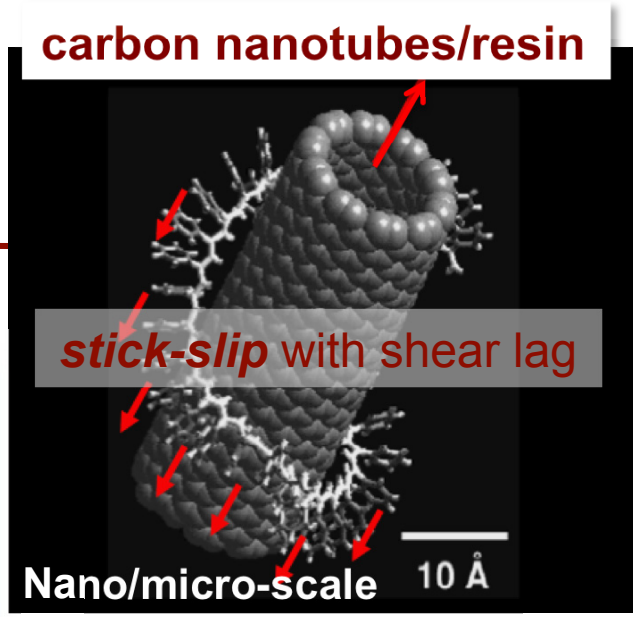
Shape memory alloy advanced modeling for industrial and biomedical applications

Mitigazione di vibrazioni mediante isteresi

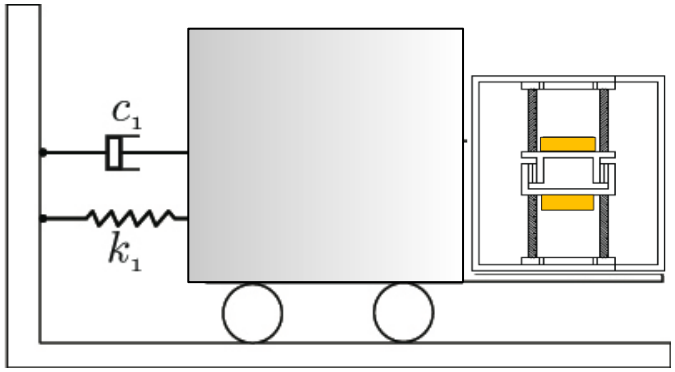


Hysteretic friction:
energy dissipation

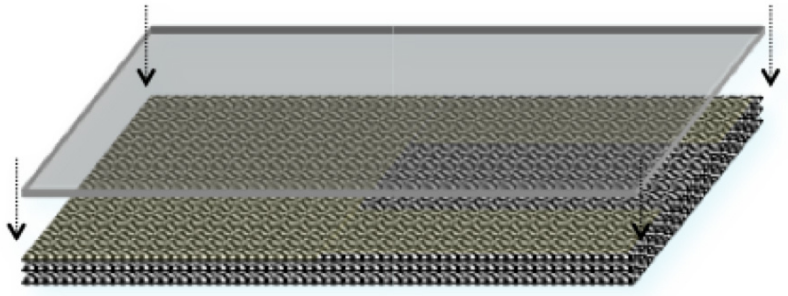




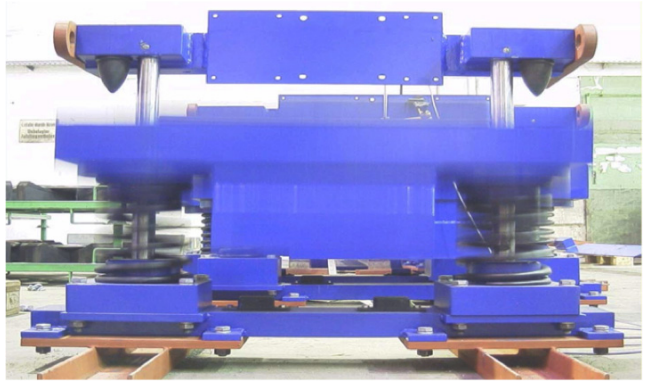
Hysteretic TMD (tuned mass damper)



CNT-resin layers in composites



Stato dell'arte sui TMD



Viscoelastic TMD

Flessibilità di utilizzo
Semplicità della progettazione
Basso costo di installazione

Rapporto di massa
0.05 – 0.001
Intervallo di frequenze
0.3 – 30 Hz

Burj al-Arab (2002)

TMD using multistage rubber bearings

Millennium Bridge (2000)

Ponte MOI (2006)

N. Masaki, Y. Suizu, T. Kamada, T. Fujita, 2004, "Development and applications of tuned/hybrid mass dampers using multi-stage rubber bearings for vibration control of structures", *13th World Conference on Earthquake Engineering Vancouver, B.C., Canada, August 1-6*, 2004 - Paper No. 2243

Stato dell'arte: Stockbridge damper

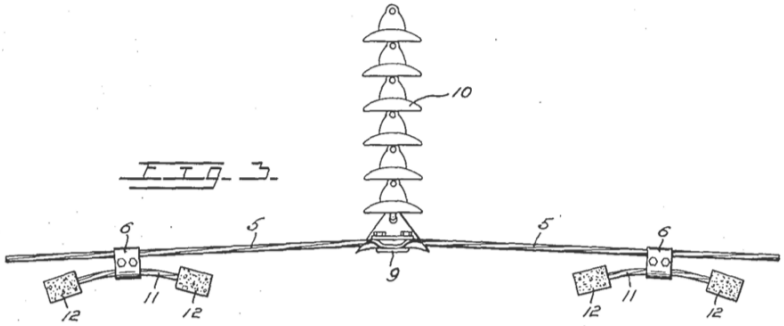
Patented July 3, 1928. 1,675,391

UNITED STATES PATENT OFFICE.

GEORGE H. STOCKBRIDGE, OF LOS ANGELES, CALIFORNIA.

VIBRATION DAMPER.

Application filed November 12, 1925. Serial No. 68,634.



Stockbridge damper

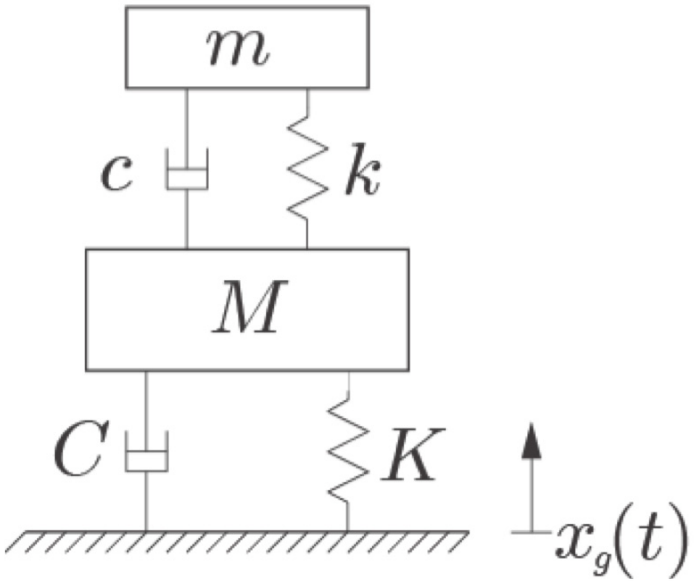
G. H. Stockbridge, 1928, "Vibration damper", U.S. Patent 1,675,391

TMD lineare vs. TMD isteretico

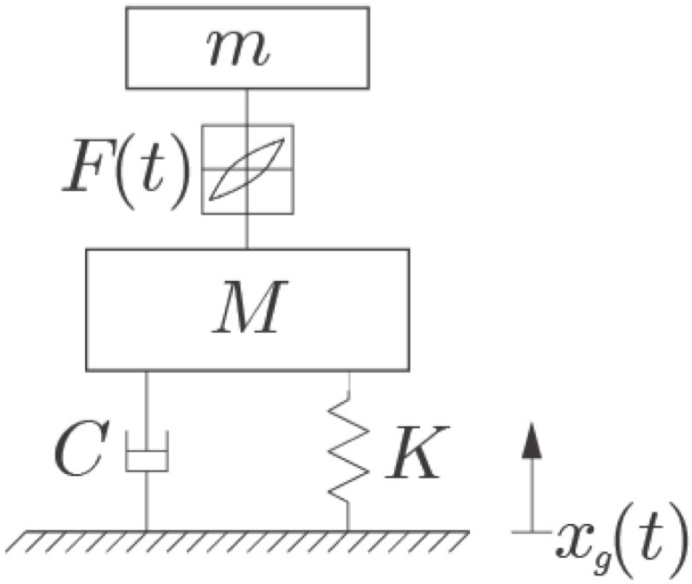
Utilizzo di un unico dispositivo

Descrizione del legame isteretico attraverso il modello di Bouc-Wen

Viscoelastic TMD



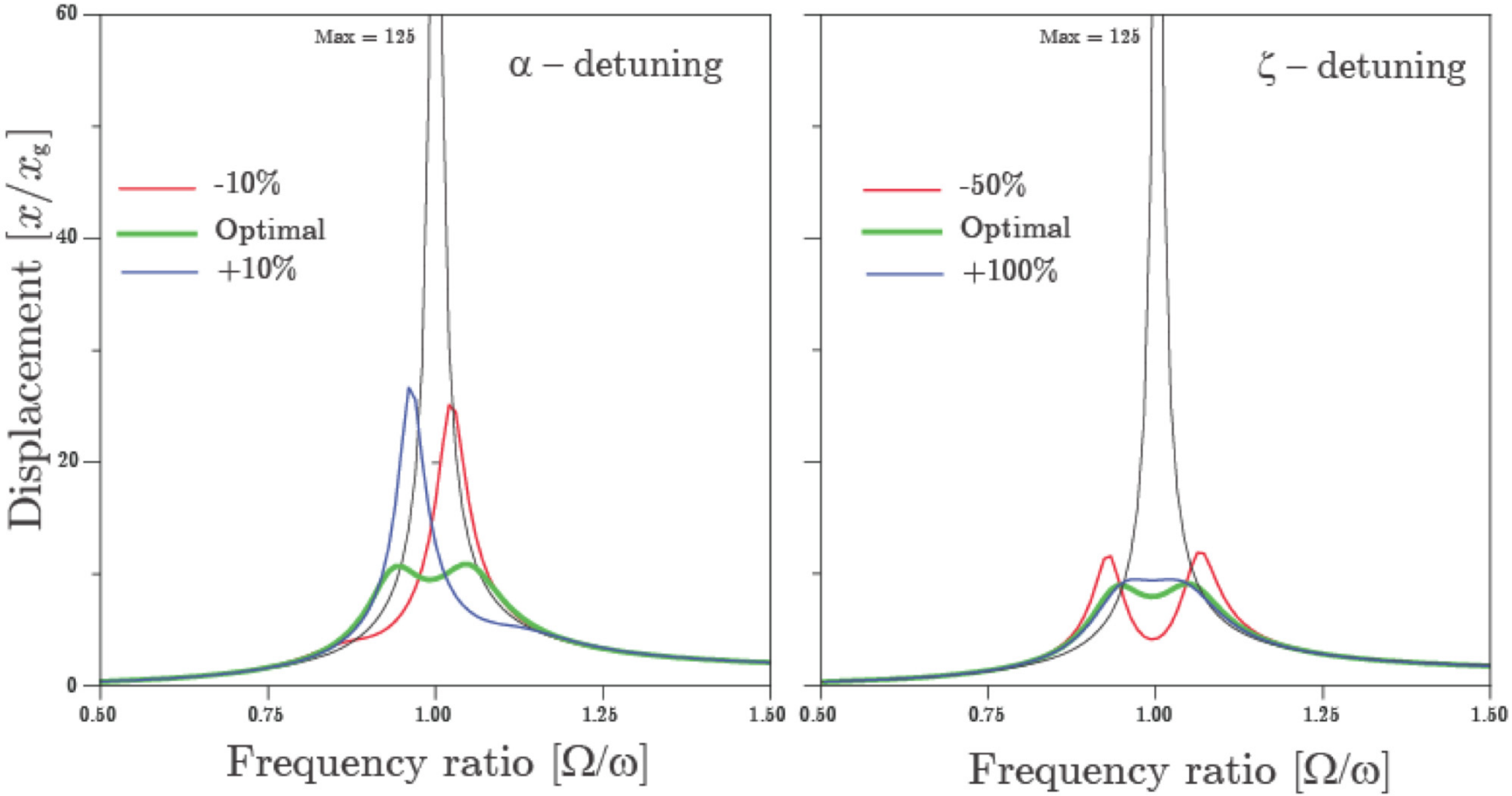
Hysteretic TMD



W. Lacarbonara, F. Vestroni, "Feasibility of a vibration absorber based on hysteresis", Proc.3rd World Congress on Structural Control, Como, April 7-12th, 2002.

Prestazioni del TMD lineare

Nicola Carpineto, 2010, *Hysteretic tuned mass dampers for structural vibration mitigation*
Dottorato di ricerca in Ingegneria delle Strutture – XXII ciclo.

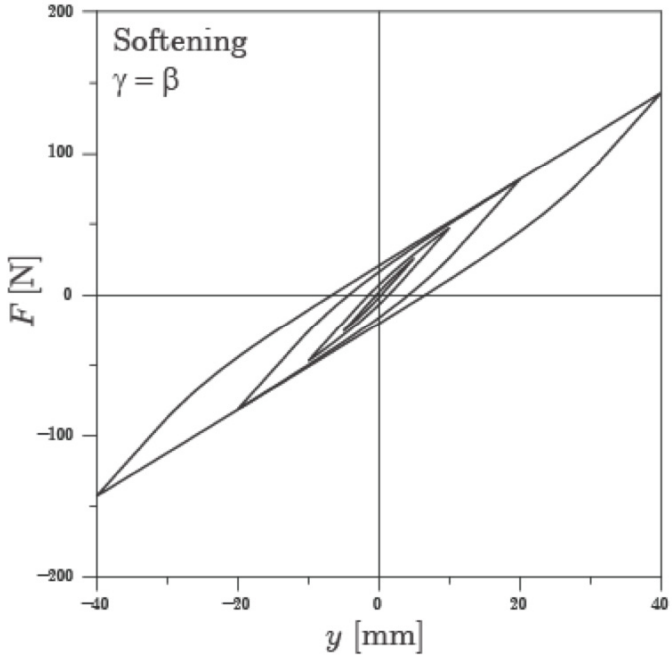


Mass ratio 2%, Frequency ratio: 0.98, Damping ratio: 8.6%

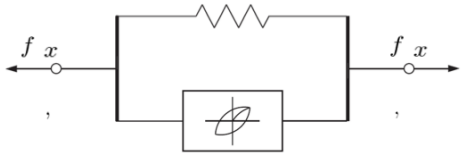
TMD isteretico: modello di Bouc-Wen

$$F = k^E y + z$$

$$z_t = \left[k^D - |z|^n \left(\gamma + \beta \, \mathrm{sgn}(y_t) \, \mathrm{sgn}(z)\right)\right] y_t$$

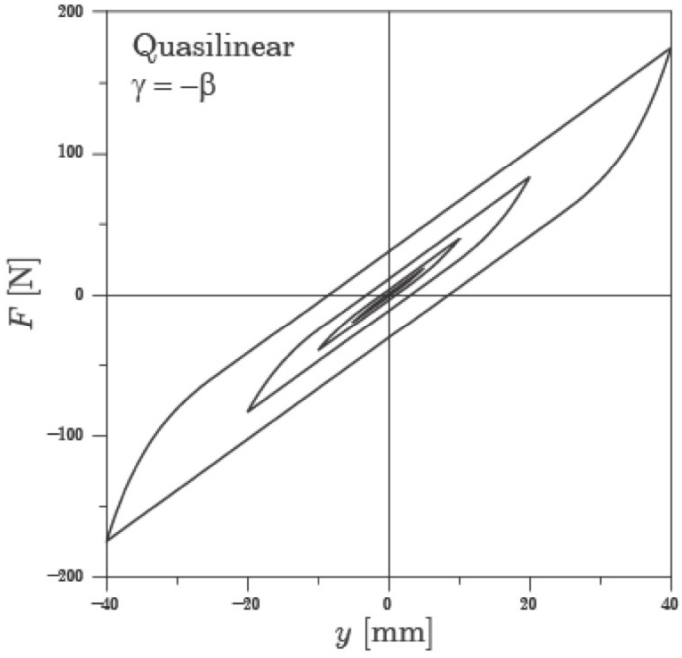


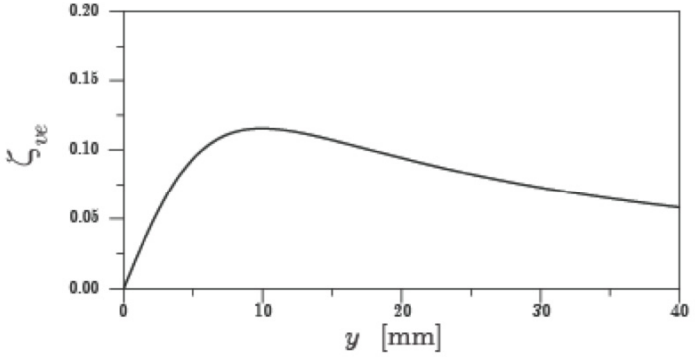
Rheological model



$$k^E, \delta, \gamma, \beta, n$$

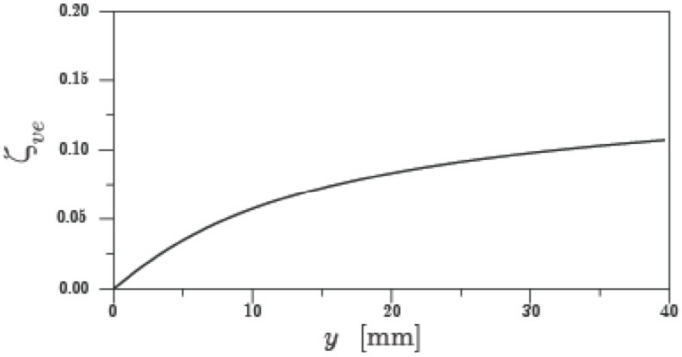
$$\delta = k^E/(k^E + k^D)$$





Equivalent damping

$$\zeta_{ve} = \frac{E_H}{2\pi y_0^2 k^E}$$

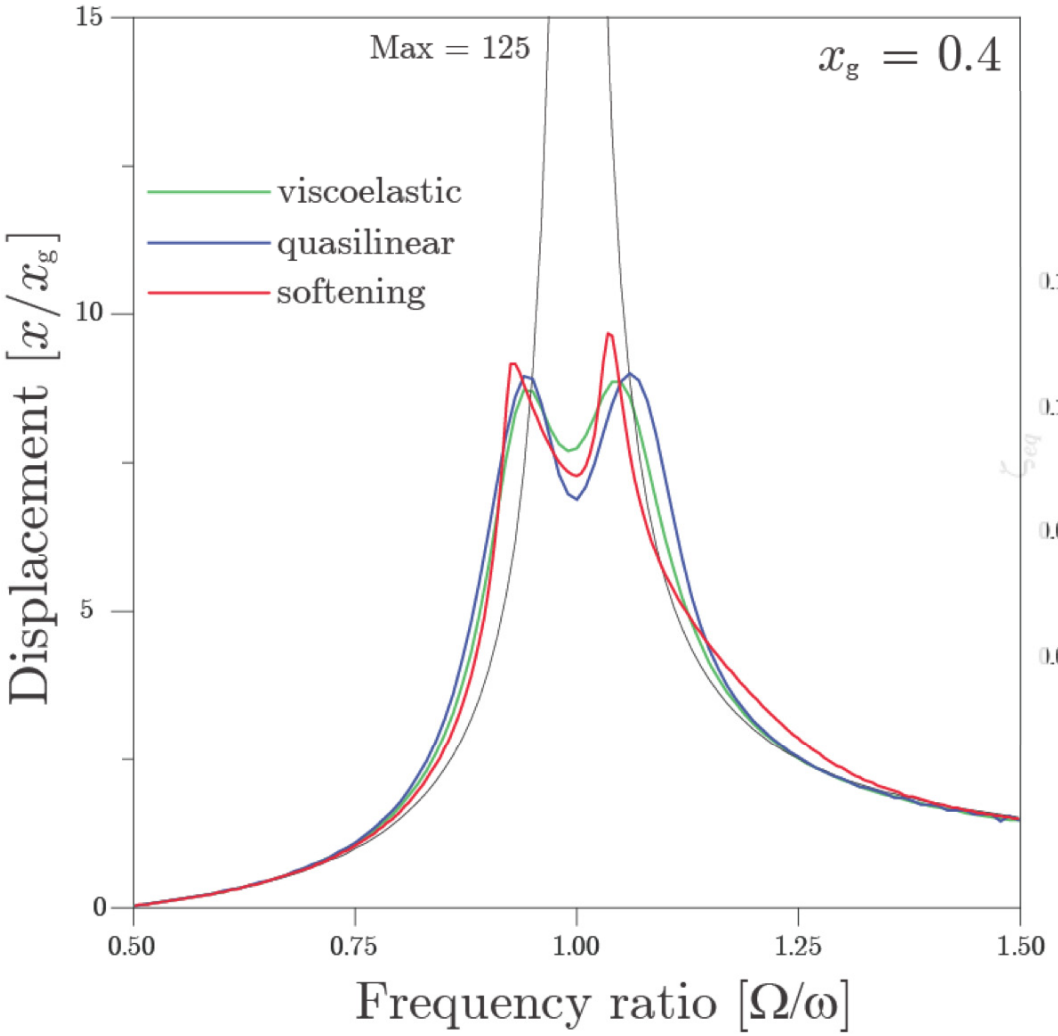


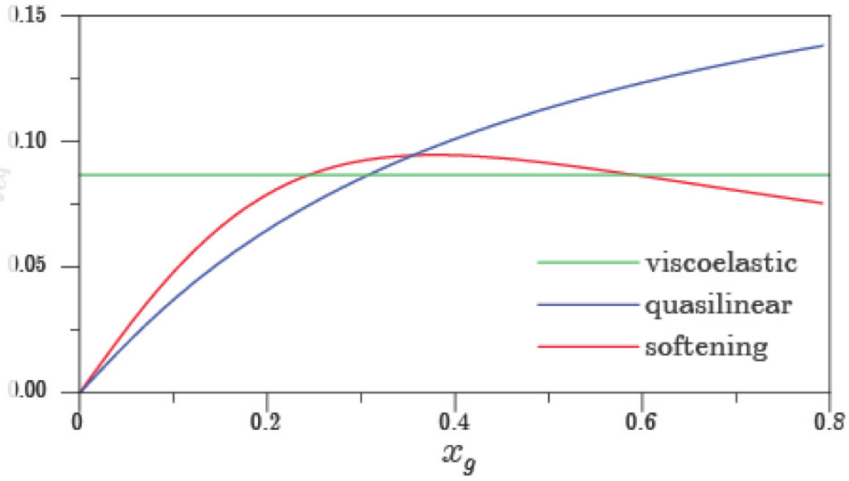
TMD isteretico in una struttura a 1 gdl

$$(1+\mu)x_{tt} + \mu y_{tt} + 2\zeta x_t + x = -(1+\mu)a_g \sin(\Omega t)$$

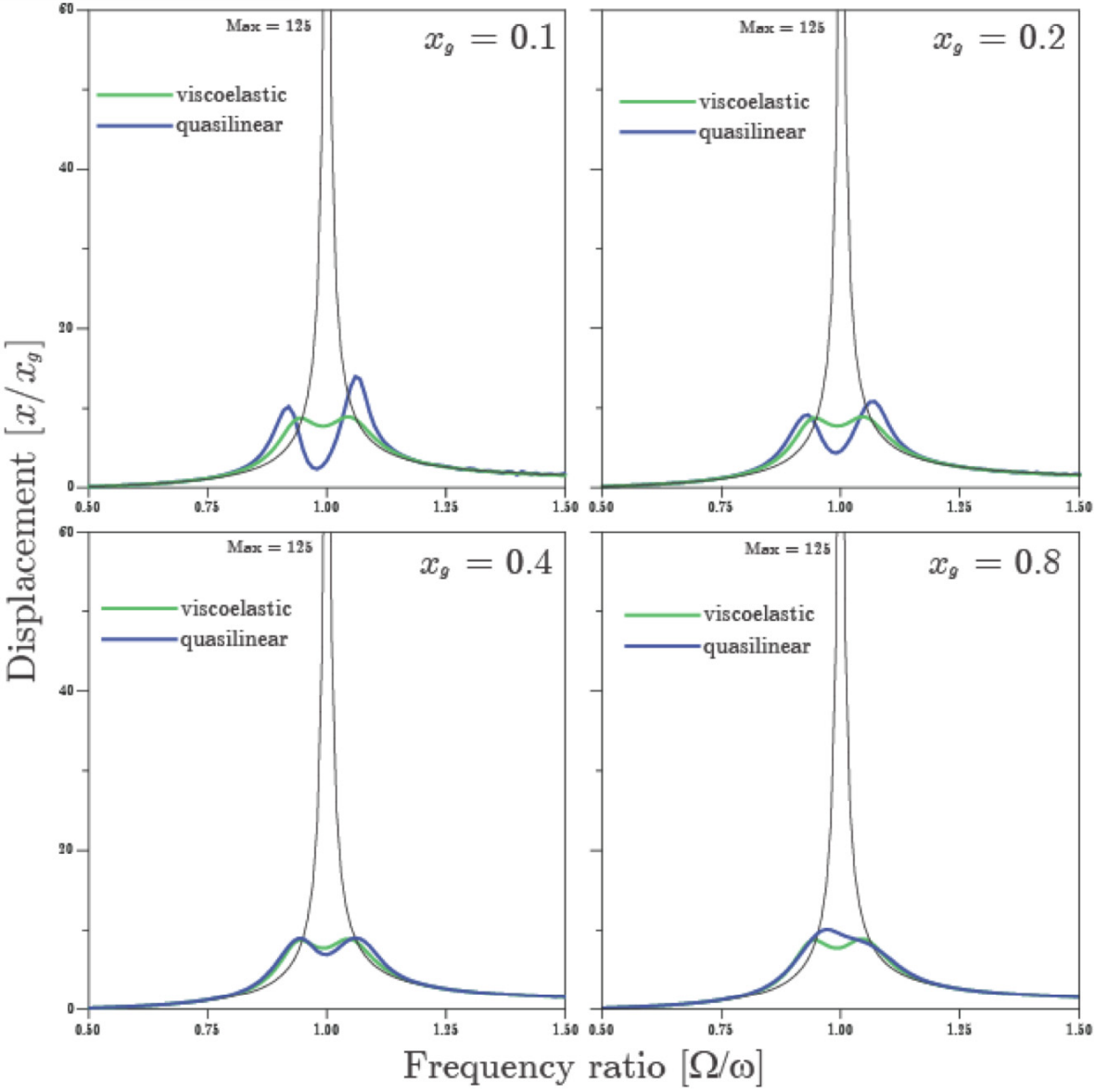
$$\mu x_{tt} + \mu y_{tt} + k\delta y = -k(1-\delta)z - \mu a_g \sin(\Omega t)$$

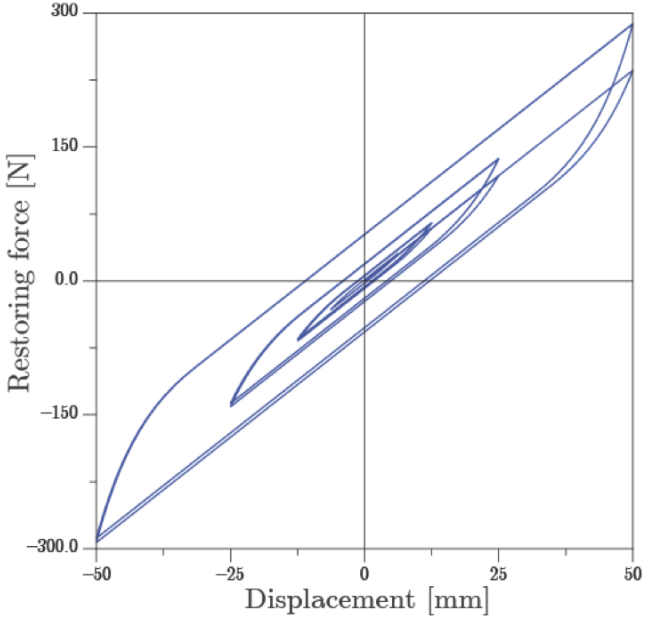
$$z_t = \left[1 - |z|^n\left(\gamma + \beta\ \mathrm{sgn}(y_t)\ \mathrm{sgn}(z)\right)\right] y_t$$

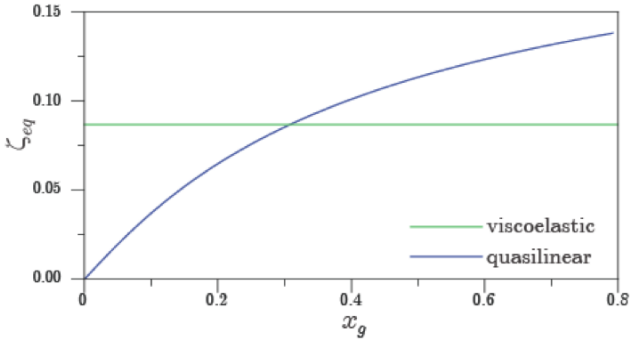




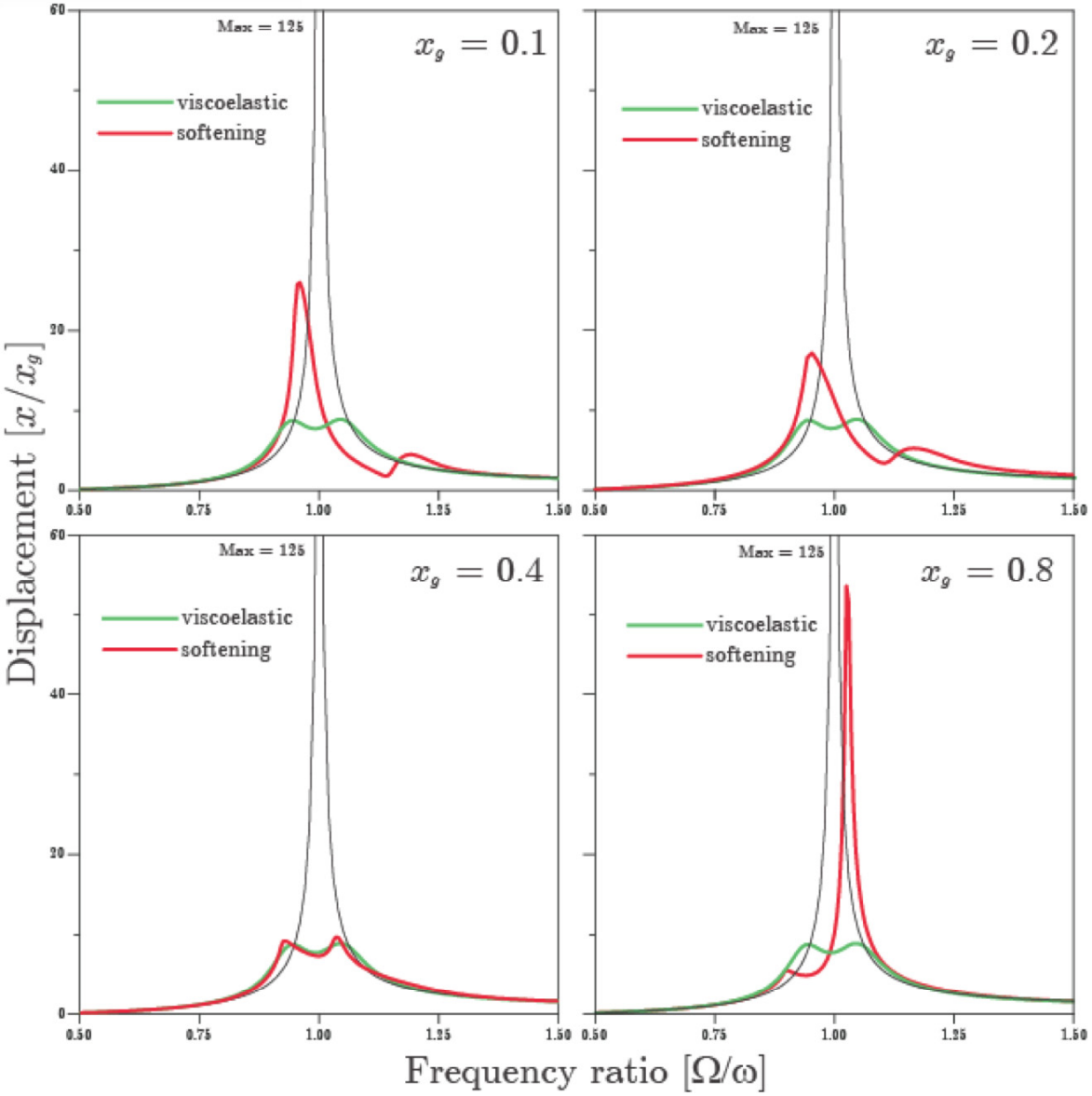
TMD isteretico (quasilineare)

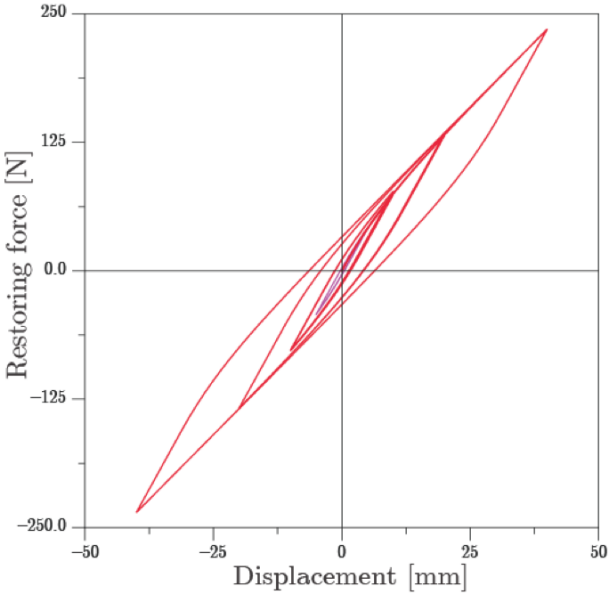


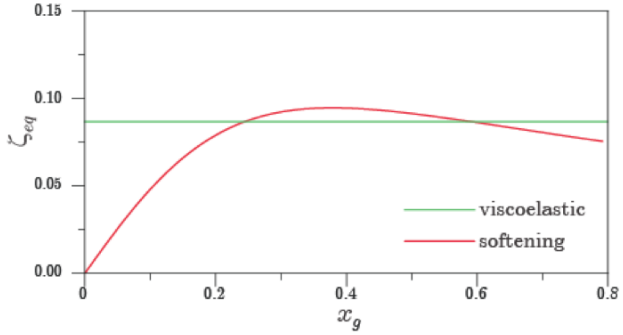




TMD isteretico (softening)







Organi isteretici

Wire-rope

Compact wire-rope

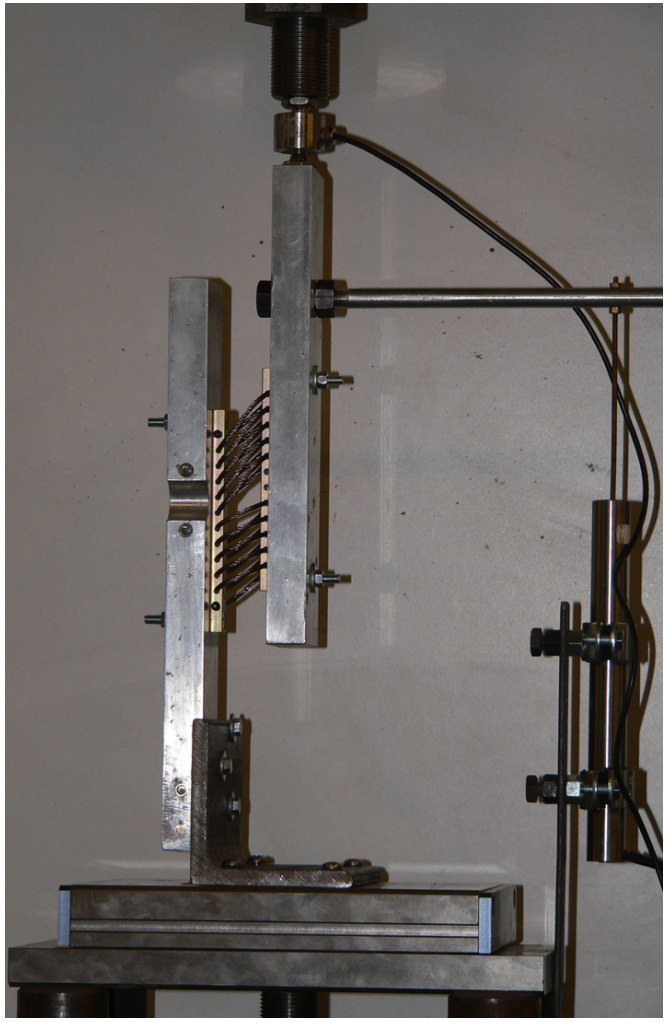
Rubber isolator

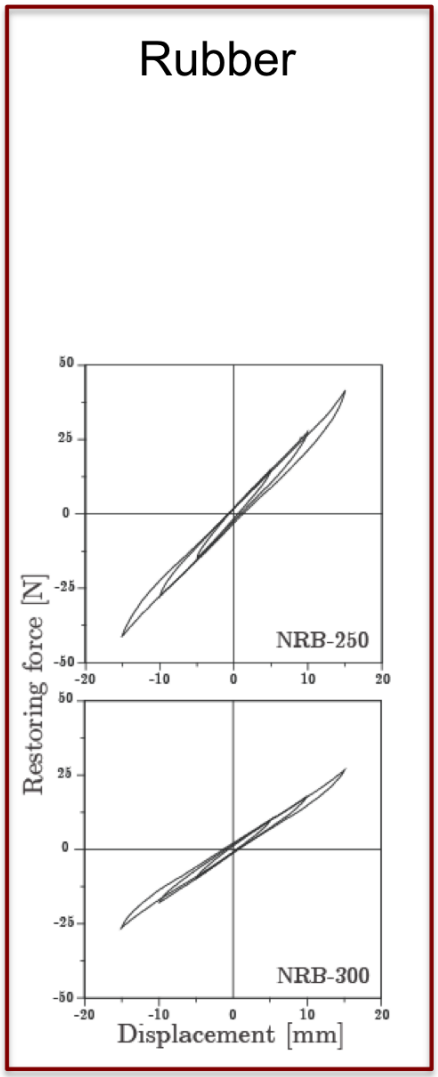
Flexural wire-rope

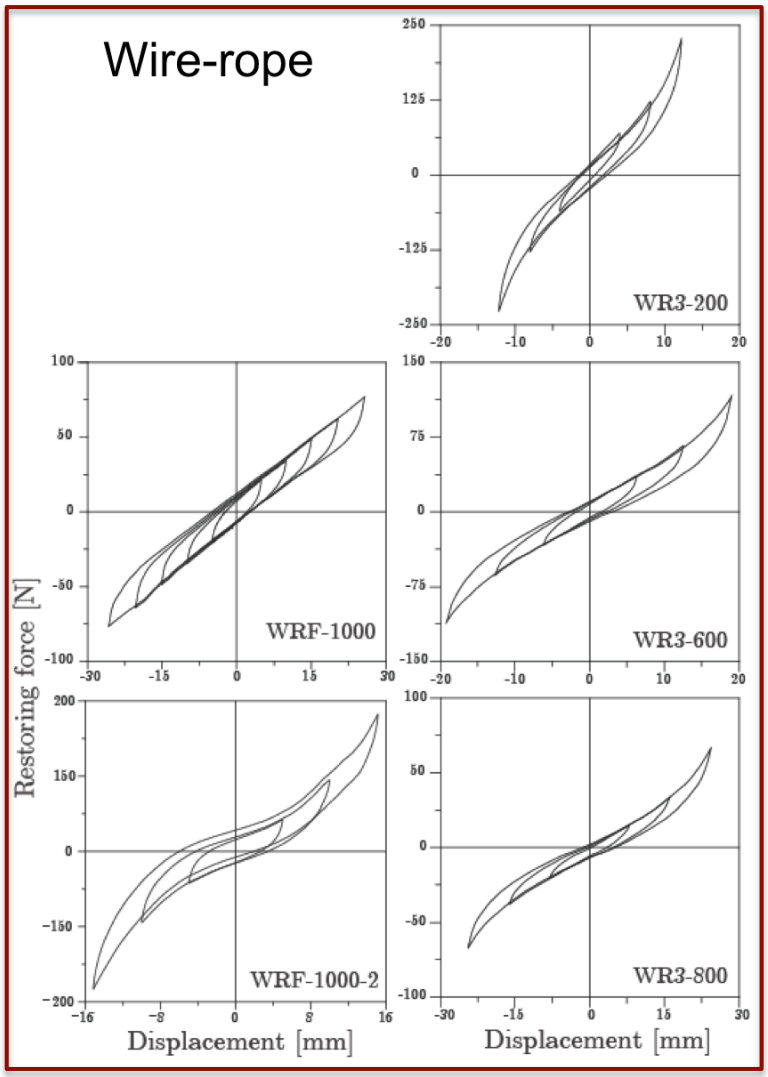
Model	*Height*	*Width*	*Isolator*
WR2-100	18mm	25mm	*Wire-rope*
WR2-400	25mm	30mm	*Wire-rope*
WR2-800	33mm	38mm	*Wire-rope*
WR3-200	25mm	30mm	*Wire-rope*
WR3-600	33mm	38mm	*Wire-rope*
WR3-800	38mm	43mm	*Wire-rope*
CR4-400	75mm	68mm	*Compact Wire-rope*
CR5-400	76mm	67mm	*Compact Wire-rope*
NRB-250	25mm	10 mm	*Rubber isolator*
NRB-300	30mm	10 mm	*Rubber isolator*
WRF-1000	100mm	100mm	*Flexural Wire-rope*
WRF-1000-2	100mm	100mm	*Flexural Wire-rope (double)*

Prove cicliche su dispositivi isteretici

Test layout

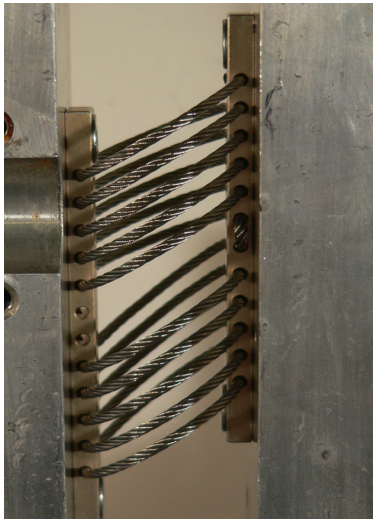


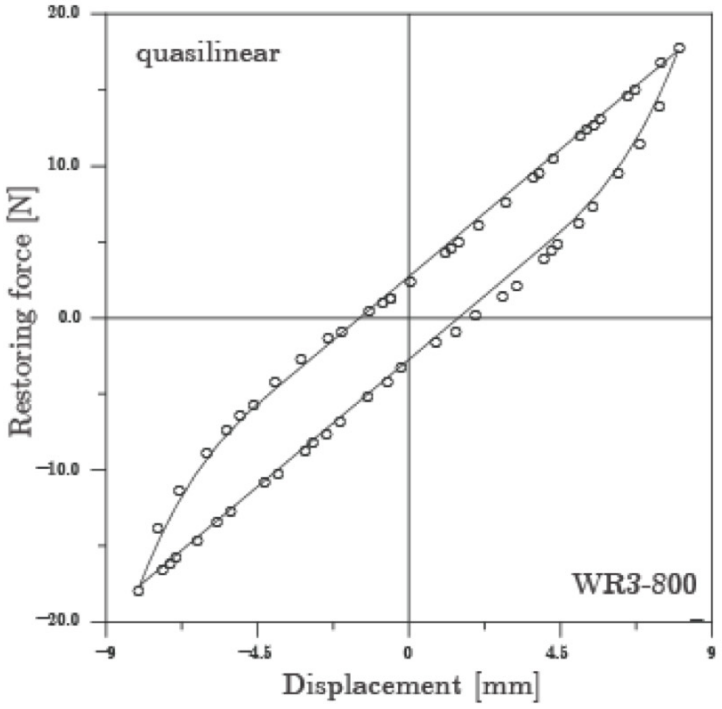


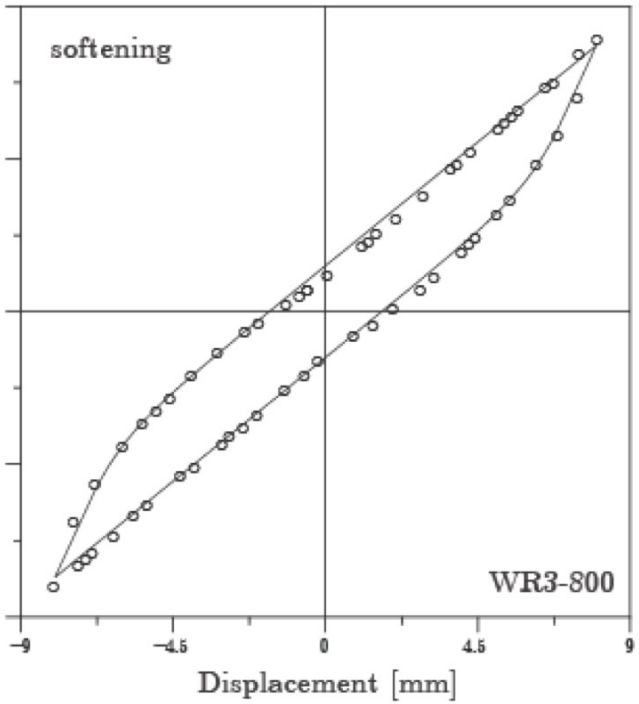


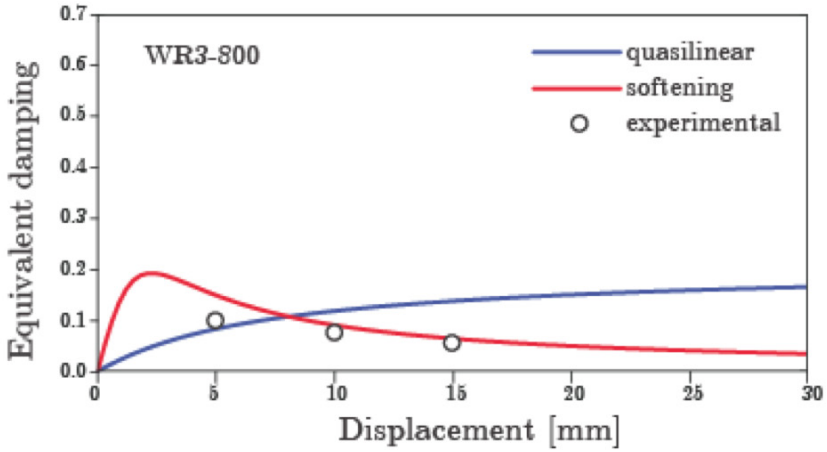
Y. Q. Ni, J. M. Ko, C. W. Wong, 1998, “Identification of non-linear hysteretic isolators from periodic vibration tests”, J. Sound Vib., 217, 737-756.

Identificazione dei parametri costitutivi









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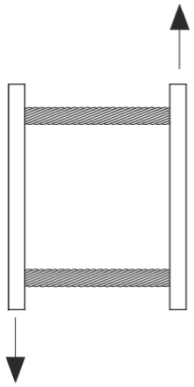
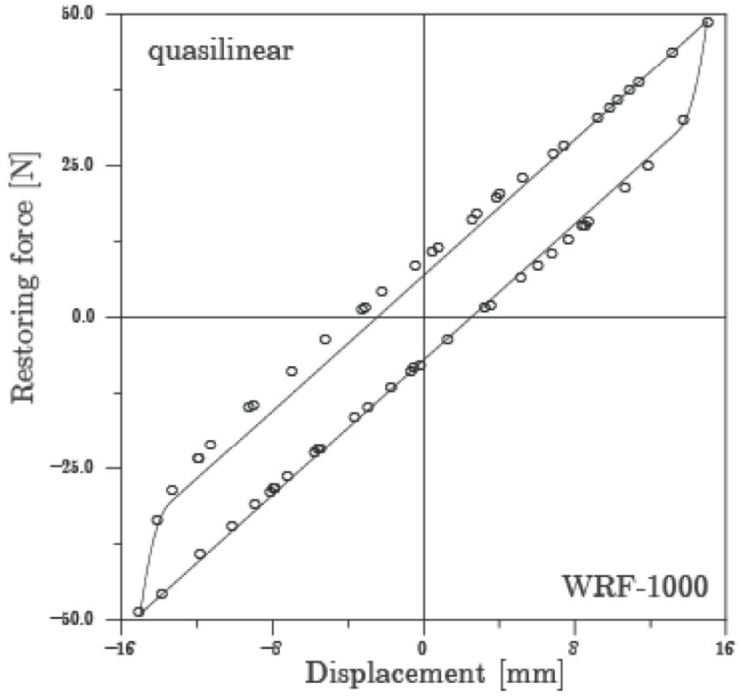
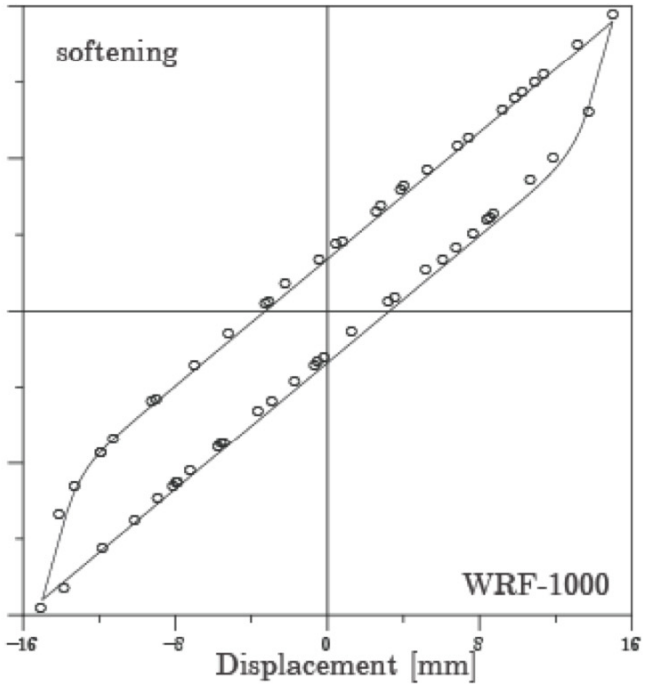
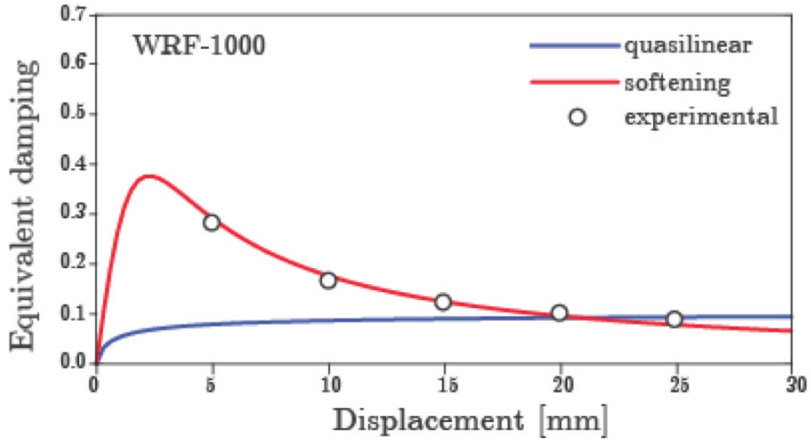
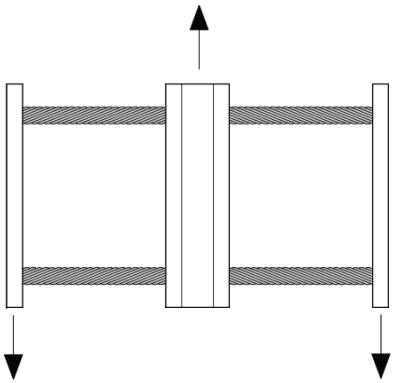


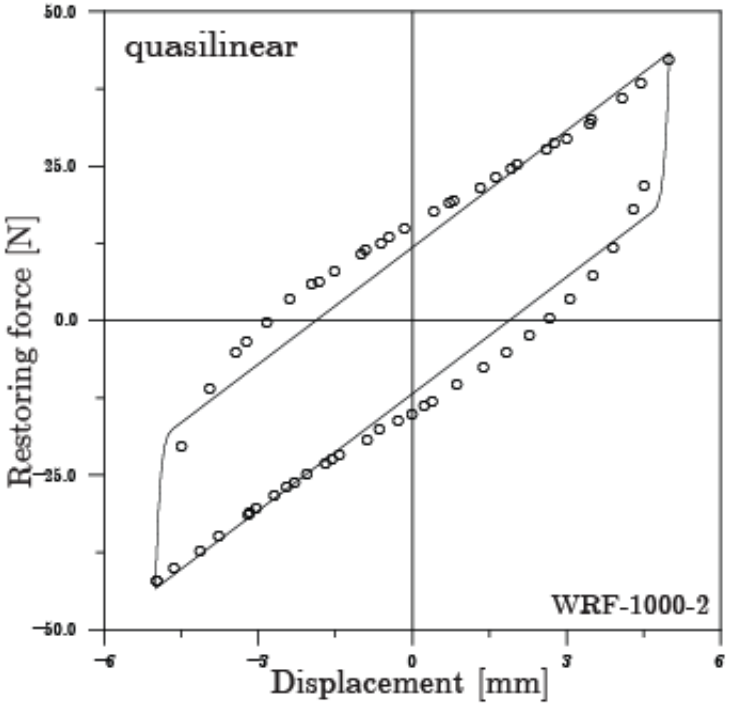


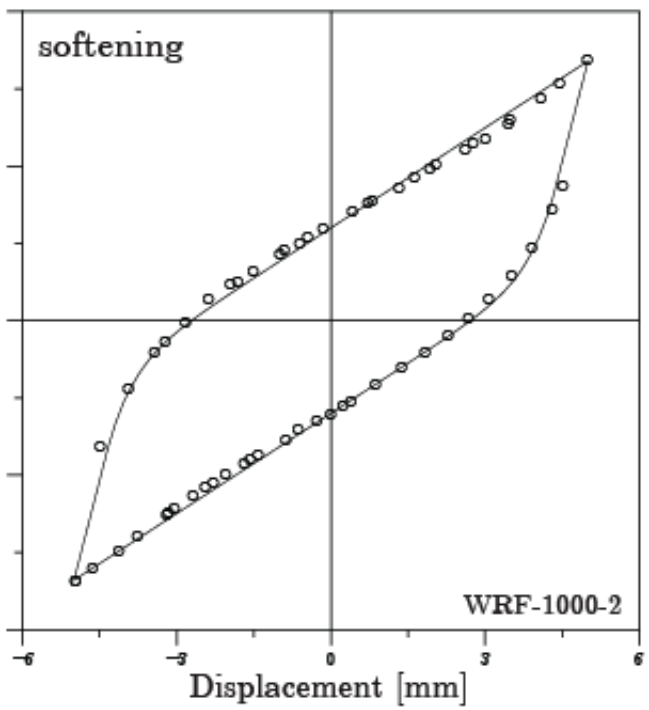


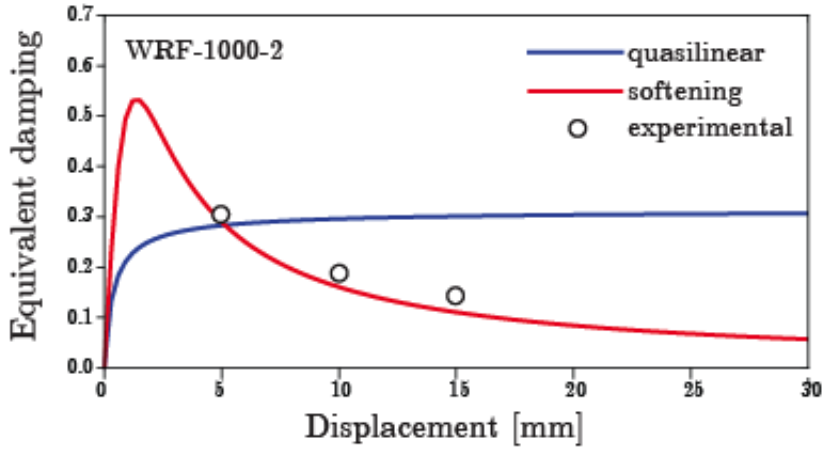


Identificazione dei parametri costitutivi









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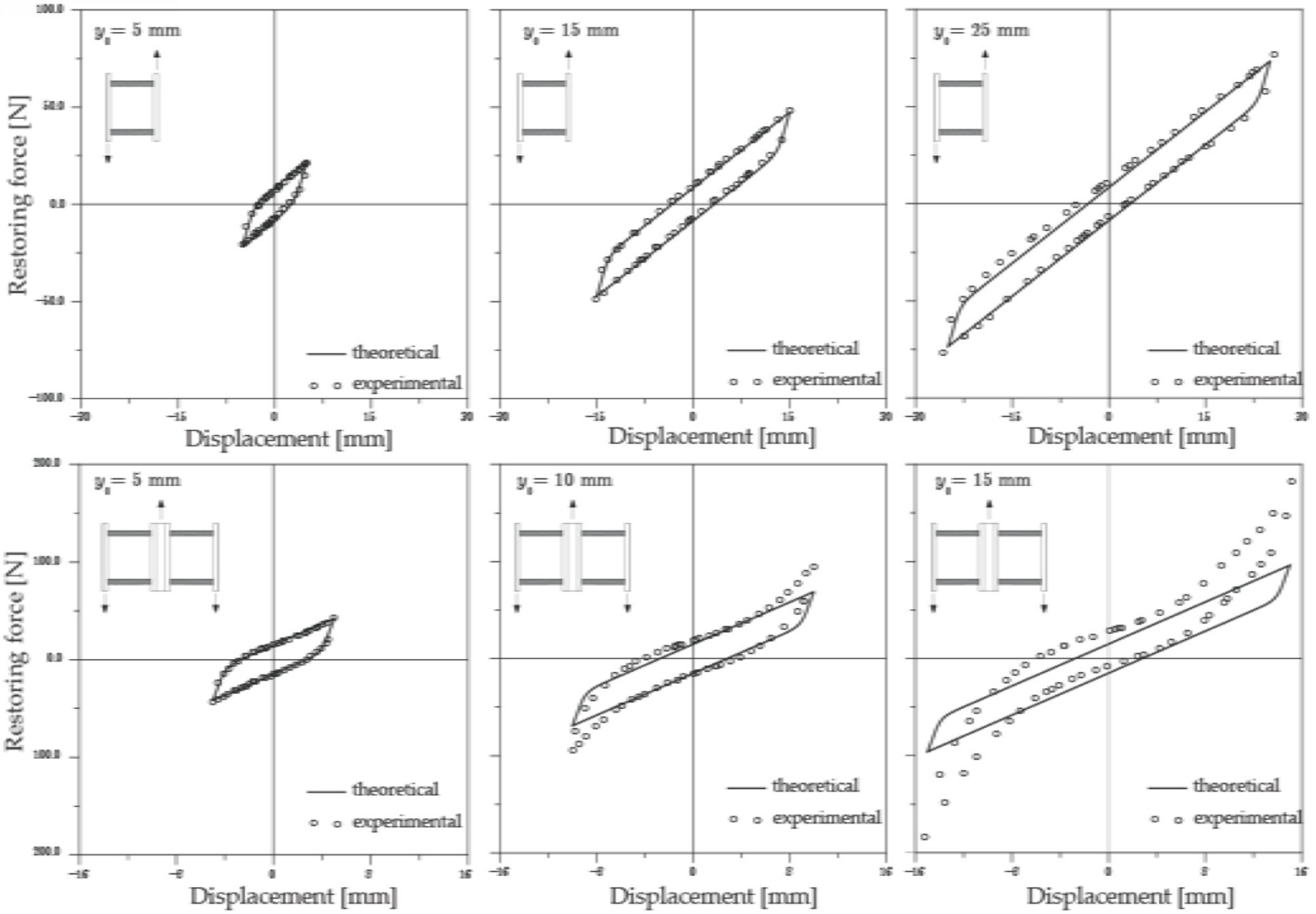
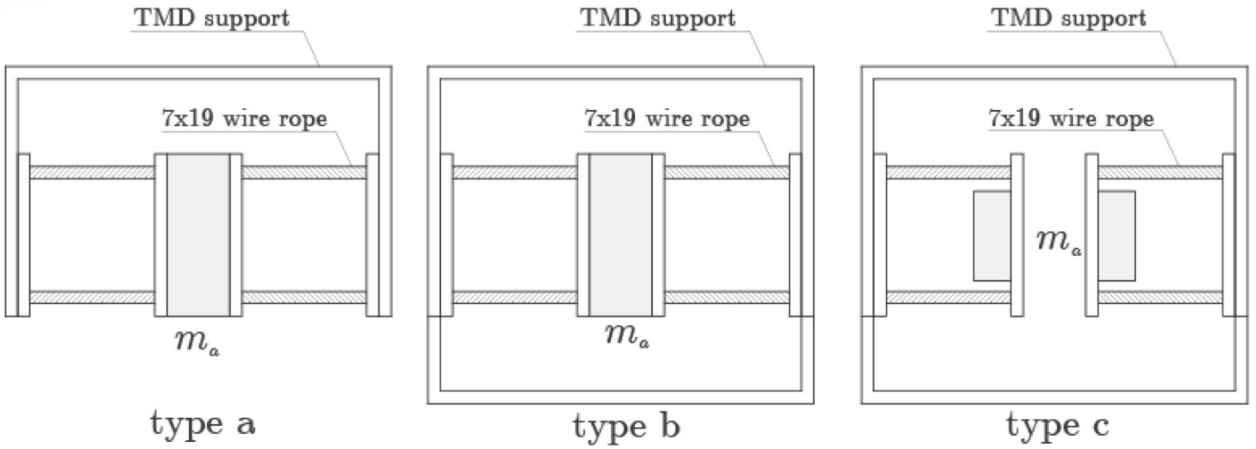
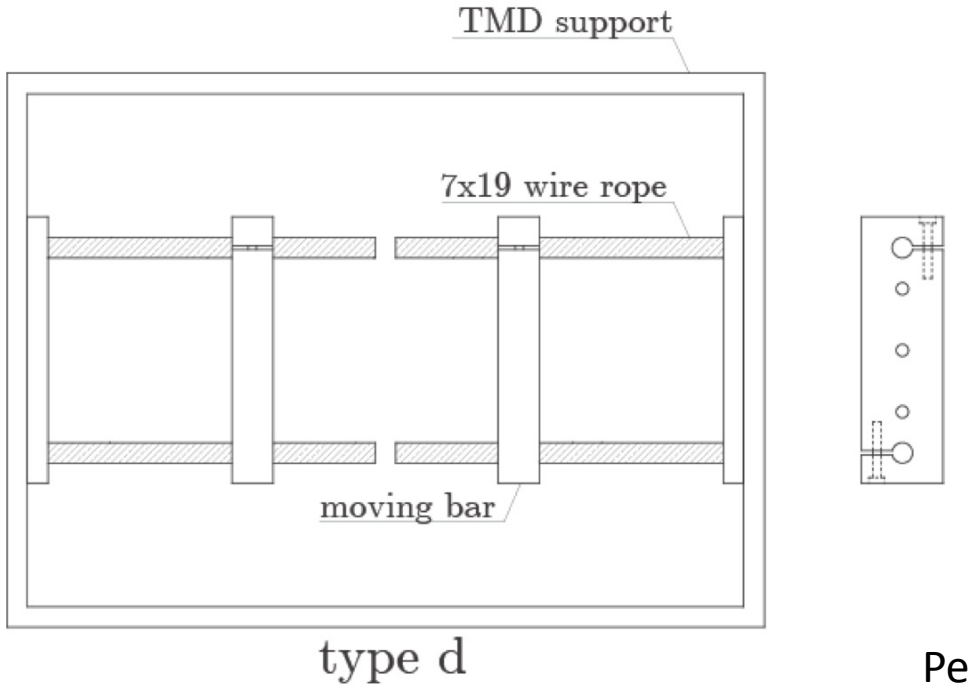
Identificazione dei parametri costitutivi



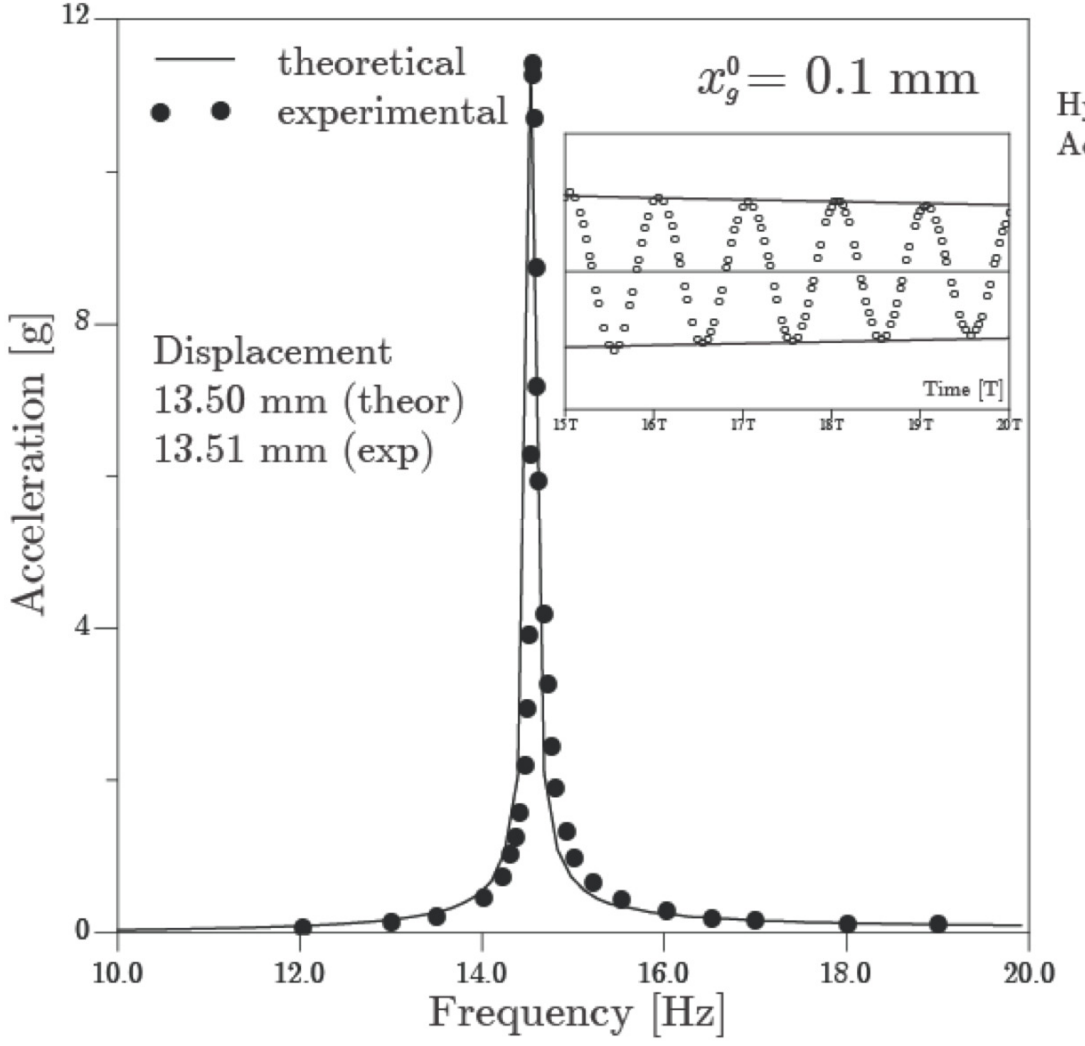
Progetto del TMD isteretico

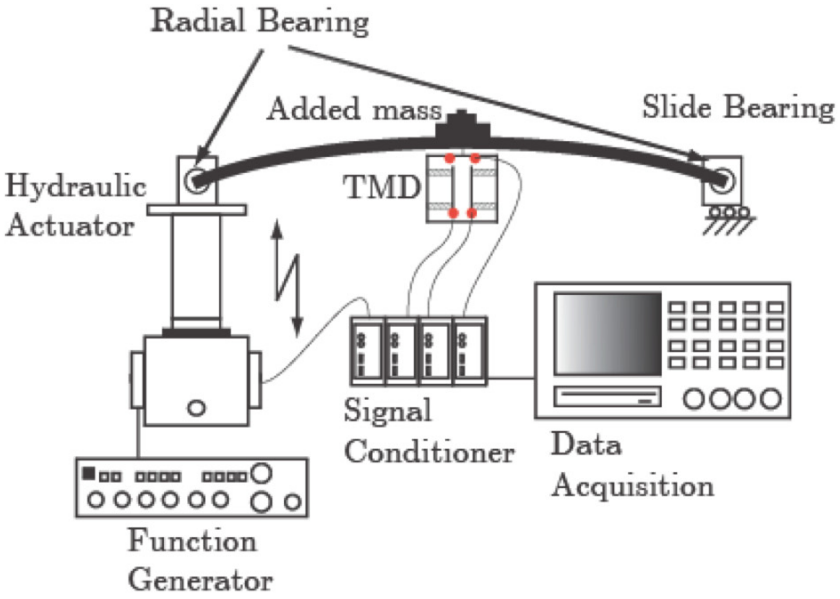




Pending patent

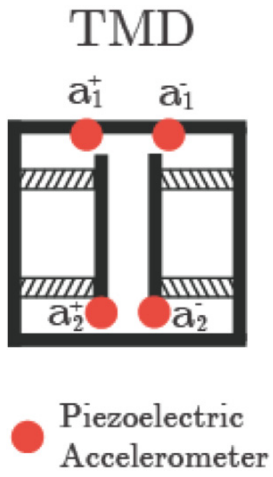
Prove sperimentali: controllo di una trave





$l = 1.20$ m
$m_b = 15.4$ kg/m
$M_{ad} = 15.0$ kg
$EI = 7168$ Nm^2
$\zeta_1 = 0.2\%$
$x_g^0 = 0.1$ - 0.7 mm

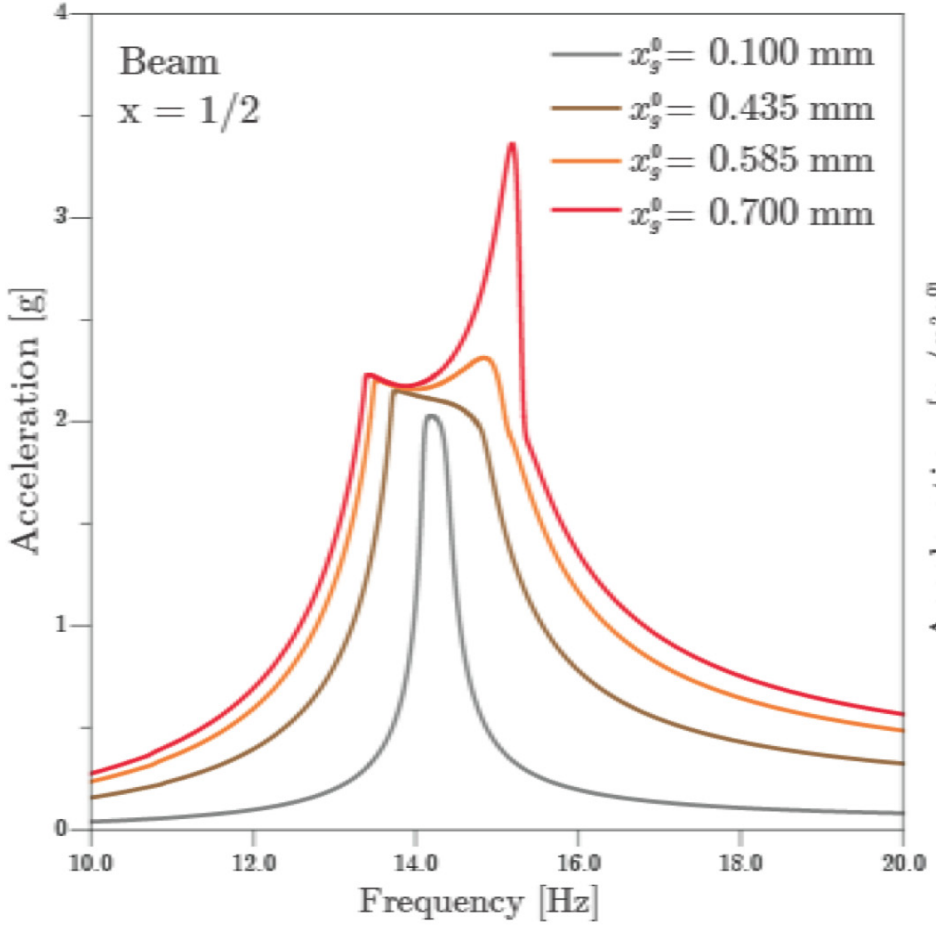
$f_1 = 14.50$ Hz
$f_2 = 94.24$ Hz

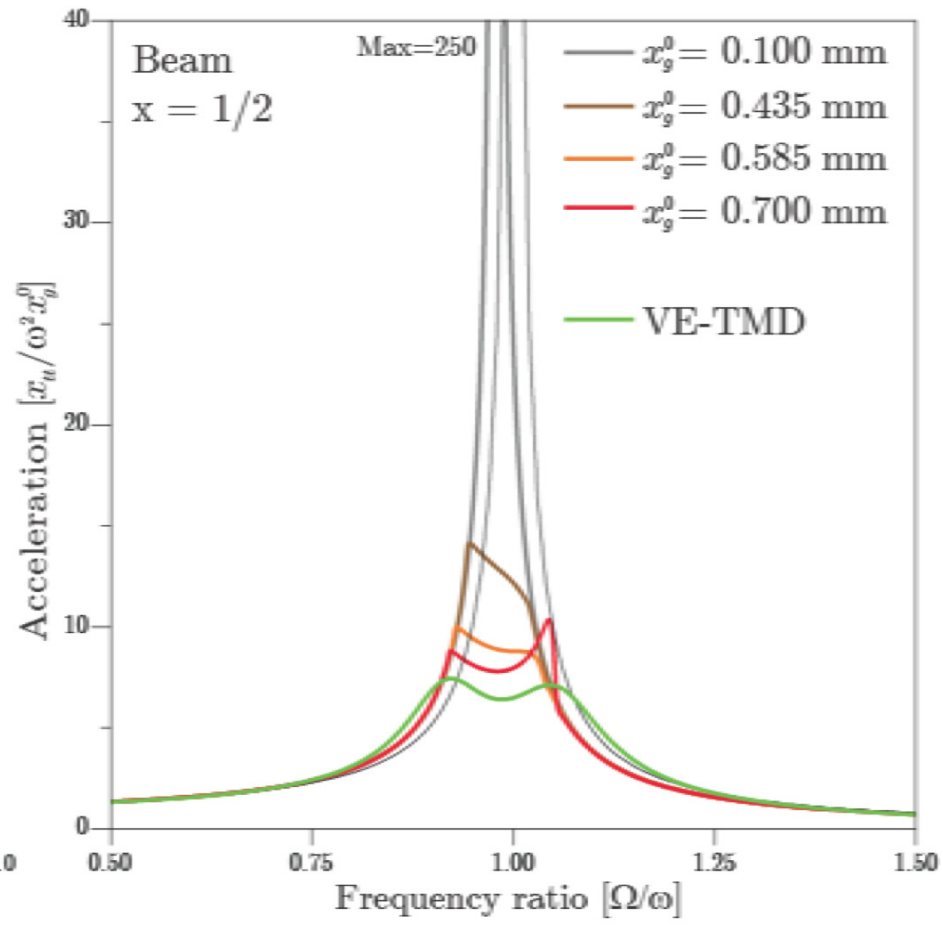


Prove sperimentali

TMD optimized for 0.7 mm base excitation

Mass ratio: 3.1%



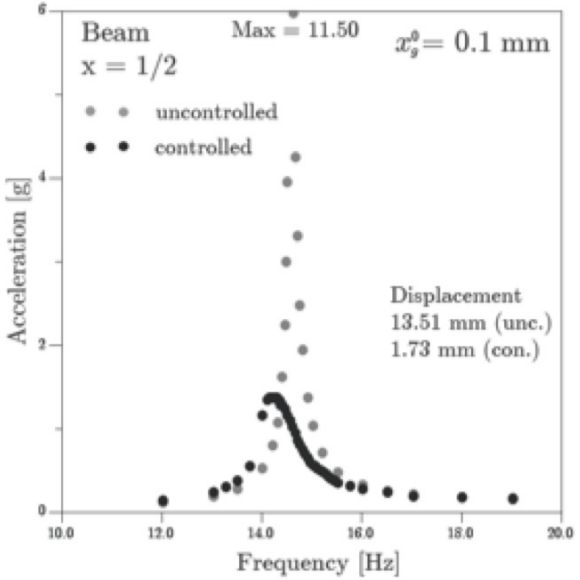


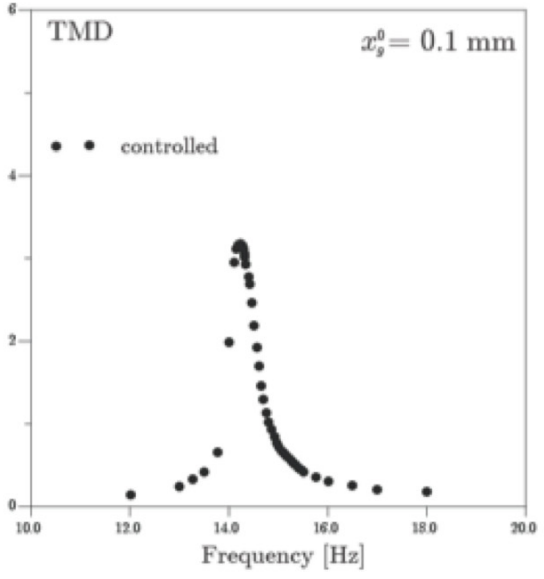
Prove sperimentali

Frequency range: 14.0 - 15.0 Hz

$x_g^0 = 0.1$ mm

$a_g^0 = 0.079$-0.092 g

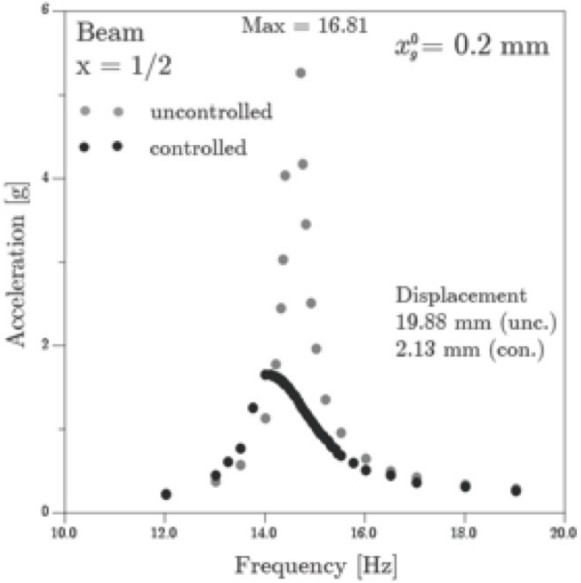


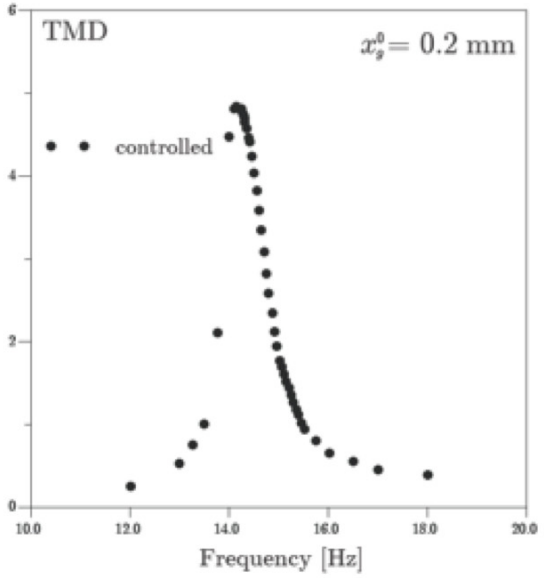


Frequency range: 14.0 - 15.0 Hz

$x_g^0 = 0.2$ mm

$a_g^0 = 0.015$-0.018 g



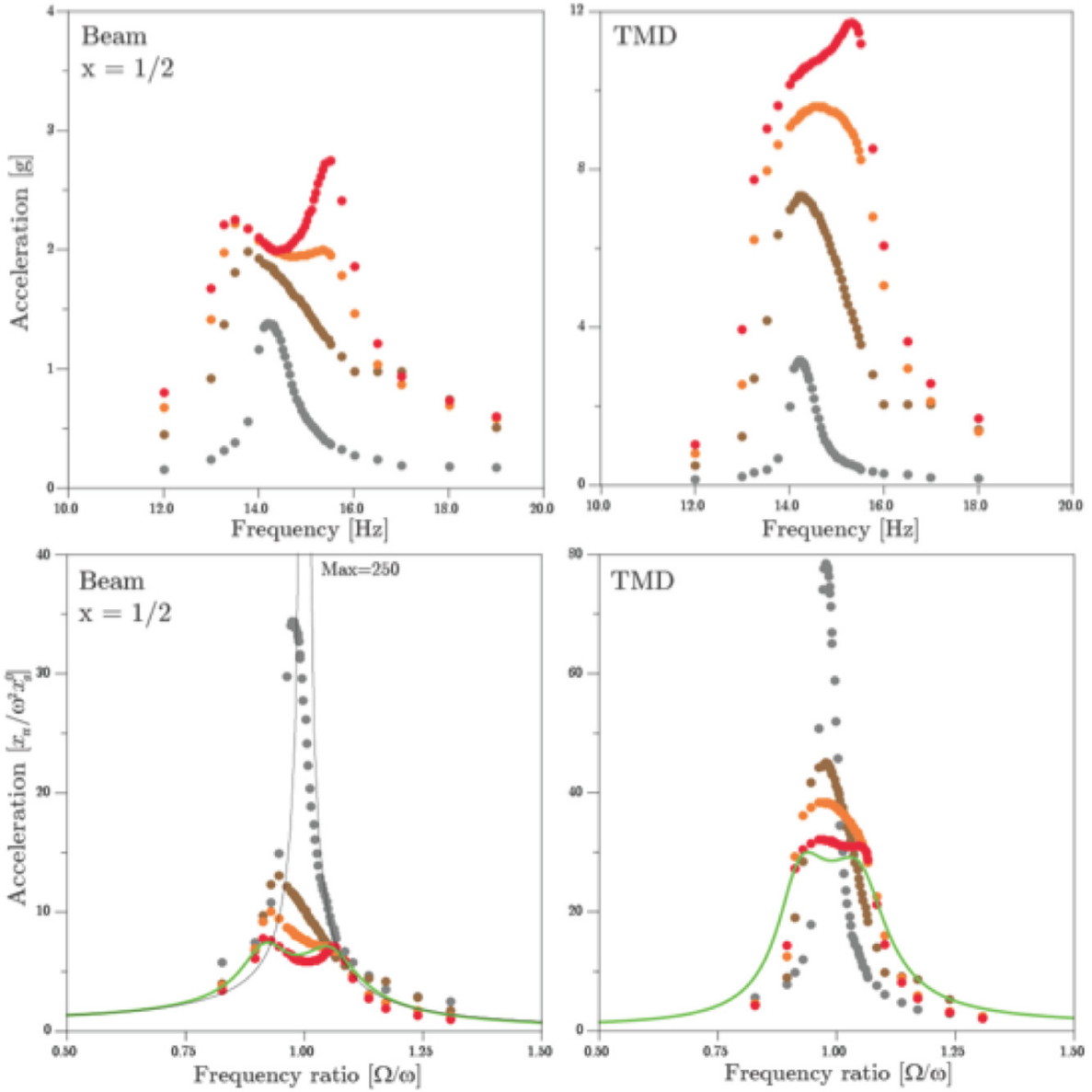


Prove sperimentali: forzante armonica

Frequency range: 14.0 - 15.0 Hz

- x_g^0= 0.100 mm a_g^0= 0.08-0.09 g
- x_g^0= 0.435 mm a_g^0= 0.32-0.36 g
- x_g^0= 0.585 mm a_g^0= 0.47-0.55 g
- x_g^0= 0.700 mm a_g^0= 0.63-0.04 g

linear visco-elastic TMD

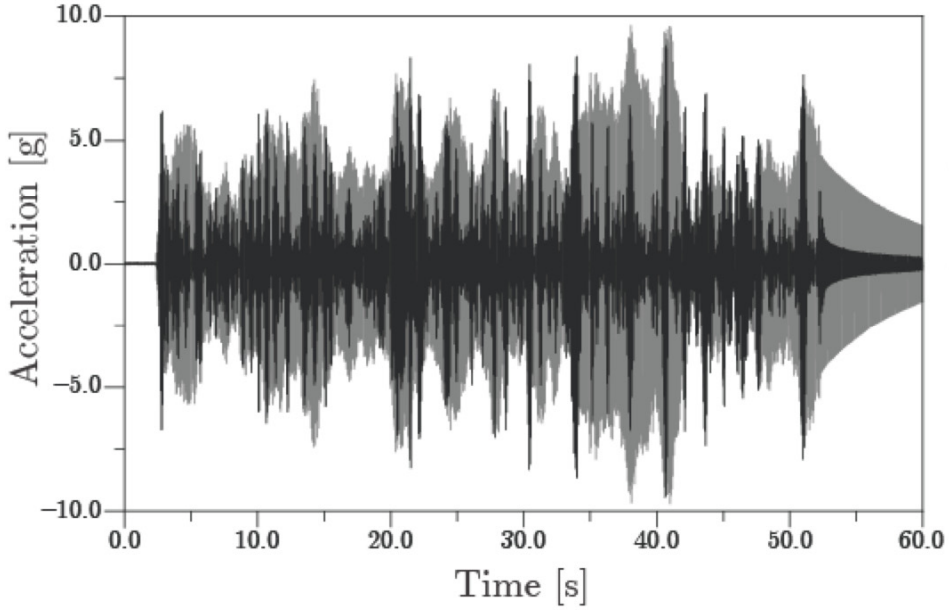


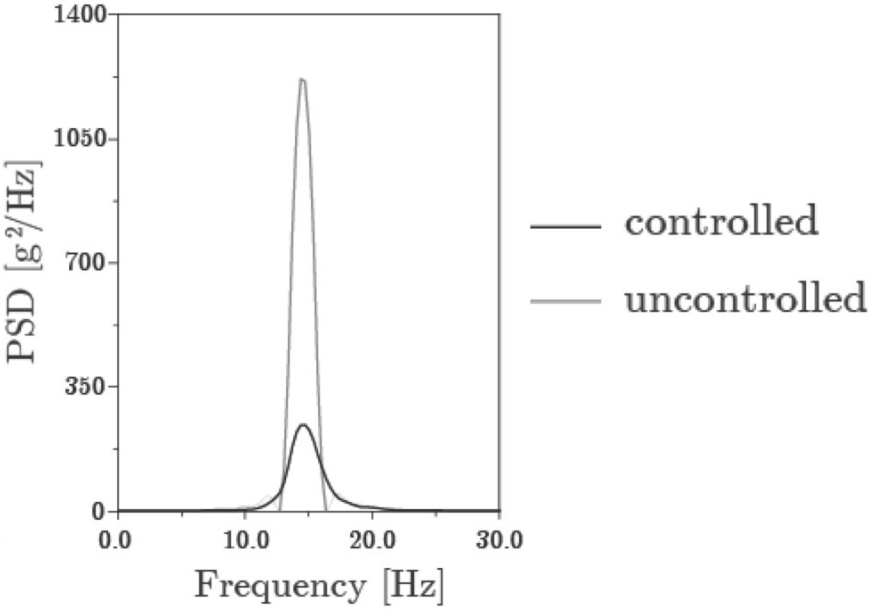
Prove sperimentali (random input signal)

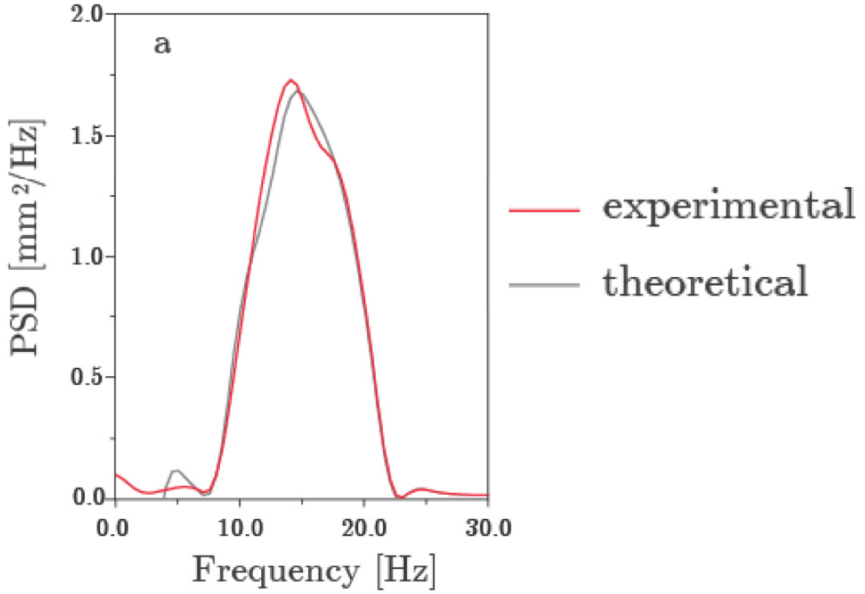
Input

Filtered white noise – [10-20] Hz

Durata: 60 s







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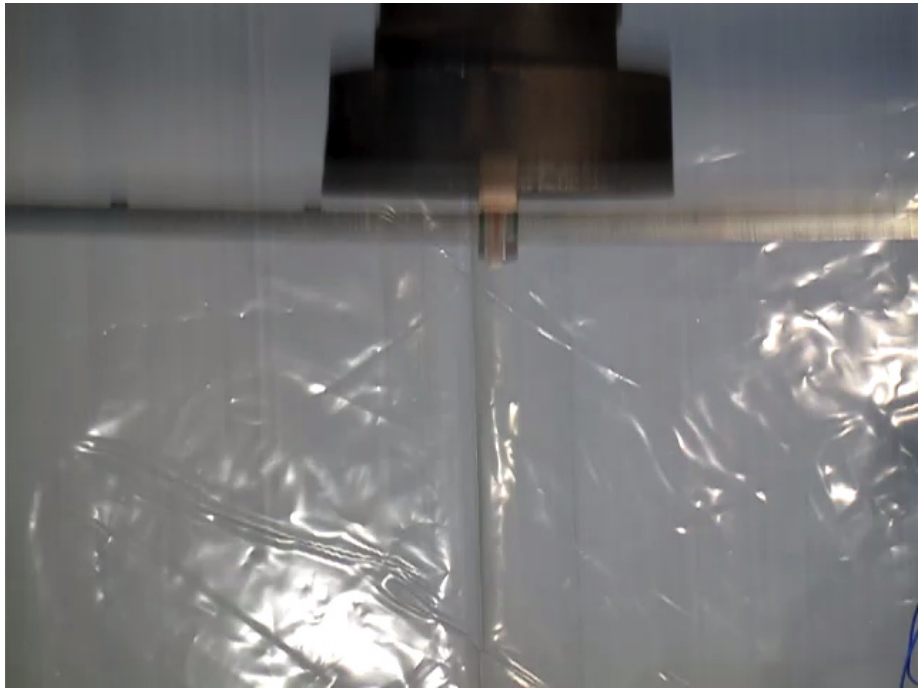
Prove sperimentali (random input signal)

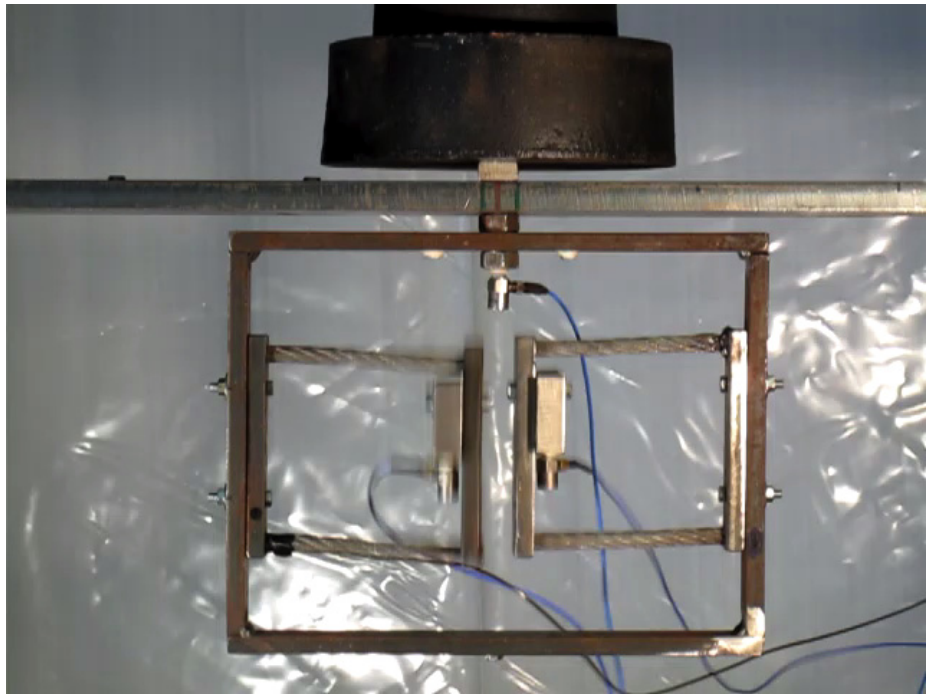
	Max			RMS		
Input	Uncontrolled [g]	Controlled [g]	Difference %	Uncontrolled [g]	Controlled [g]	Difference %
a	9.71	9.42	-3.00	3.23	1.79	-44.42
b	8.77	9.71	+10.74	2.47	1.76	-28.86
c	8.51	8.91	+4.71	2.72	1.59	-41.59
d	9.16	8.35	-8.85	2.86	1.65	-42.33
e	9.87	9.76	-2.27	3.09	1.71	-44.56
f	9.21	8.60	-6.65	2.90	1.55	-46.44
g	9.34	8.53	-8.67	3.18	1.55	-51.16
h	9.83	9.37	-4.74	3.38	1.62	-52.08
i	7.31	7.29	-0.20	2.22	1.27	-42.61
Av	9.08	8.88	-2.10	2.89	1.61	-43.78

Prove sperimentali: video

Hysteretic Vibration Absorber in Action



Uncontrolled

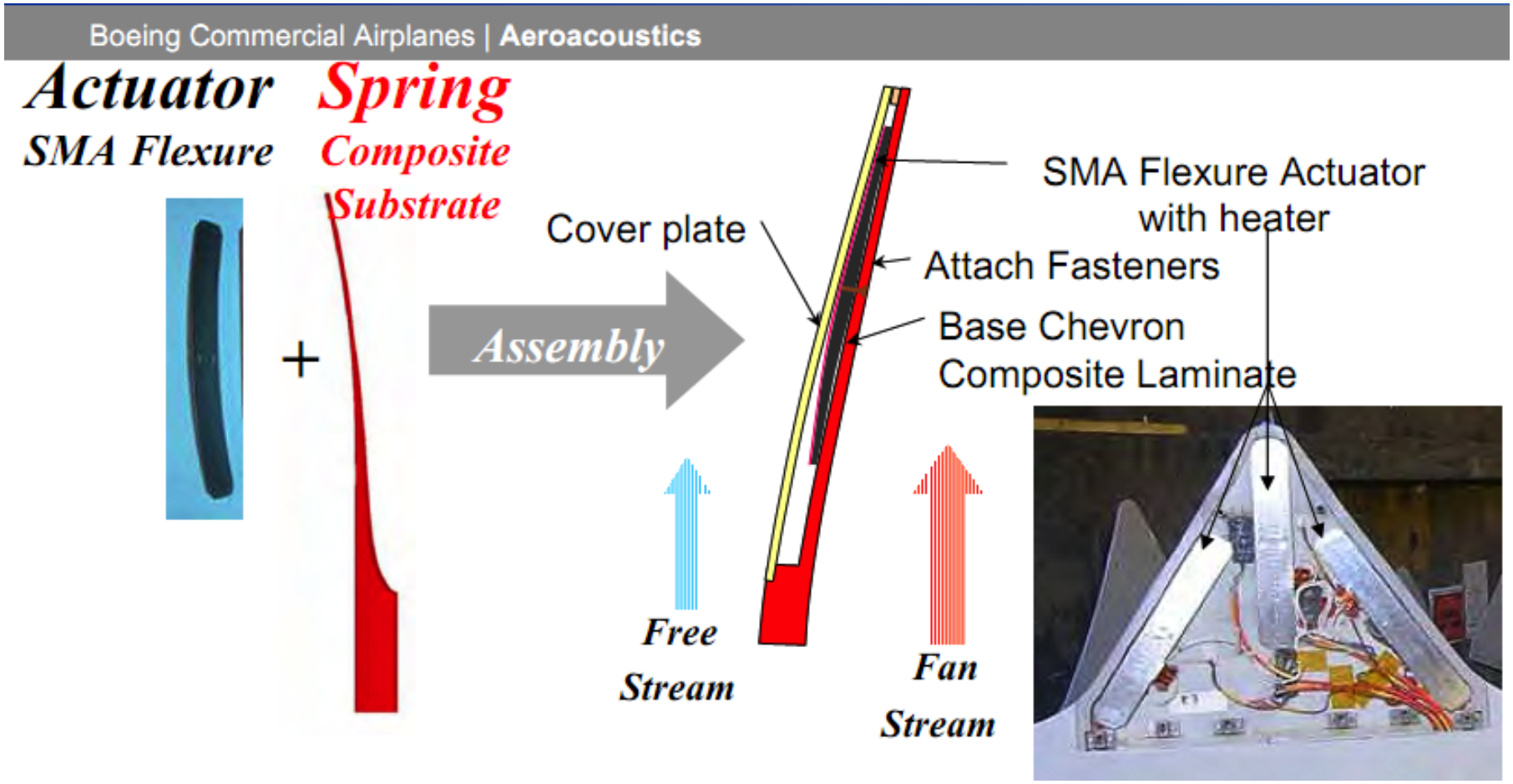


Controlled

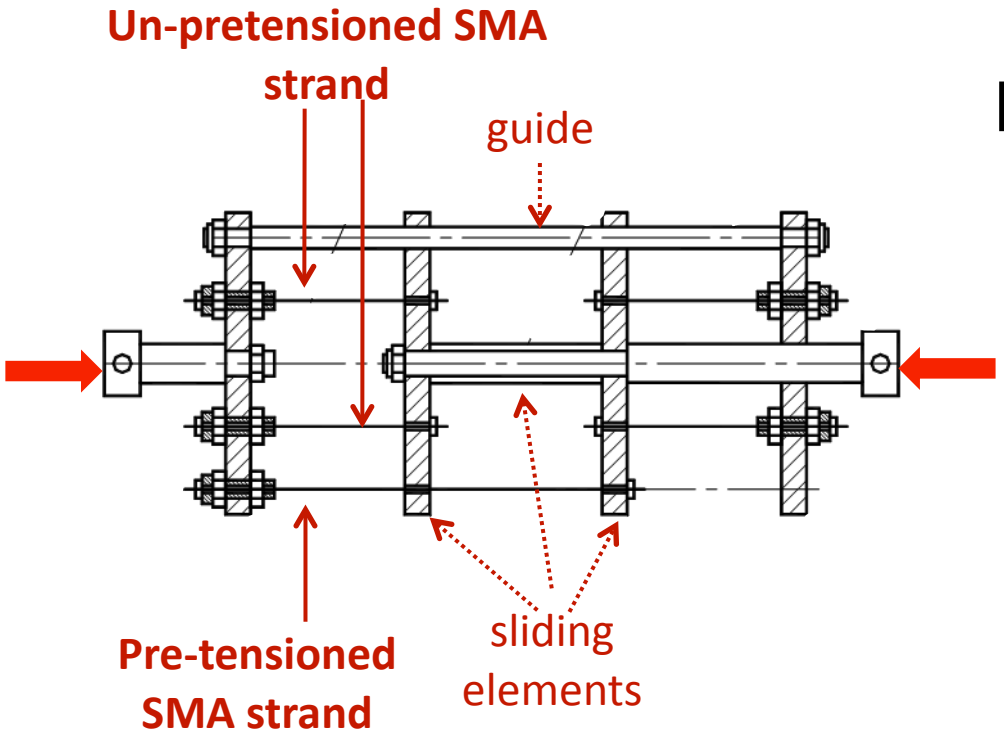
Primary resonance of the lowest mode

SAPIENZA Grants (2002, 2005, 2010) – PRIN Grant 2010, Italian Ministry of Scientific Research

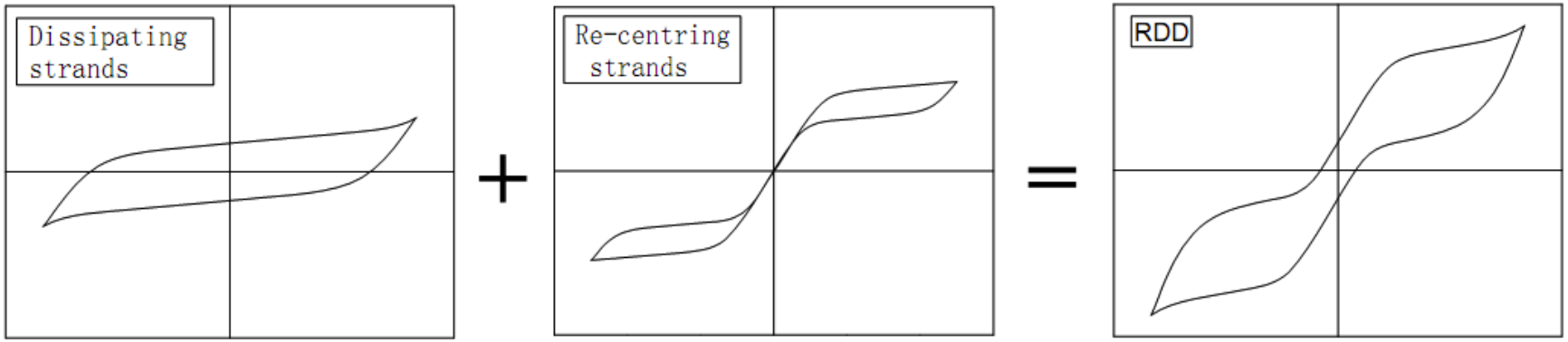
Shape Memory Alloys Applications



Shape Memory Alloys Applications

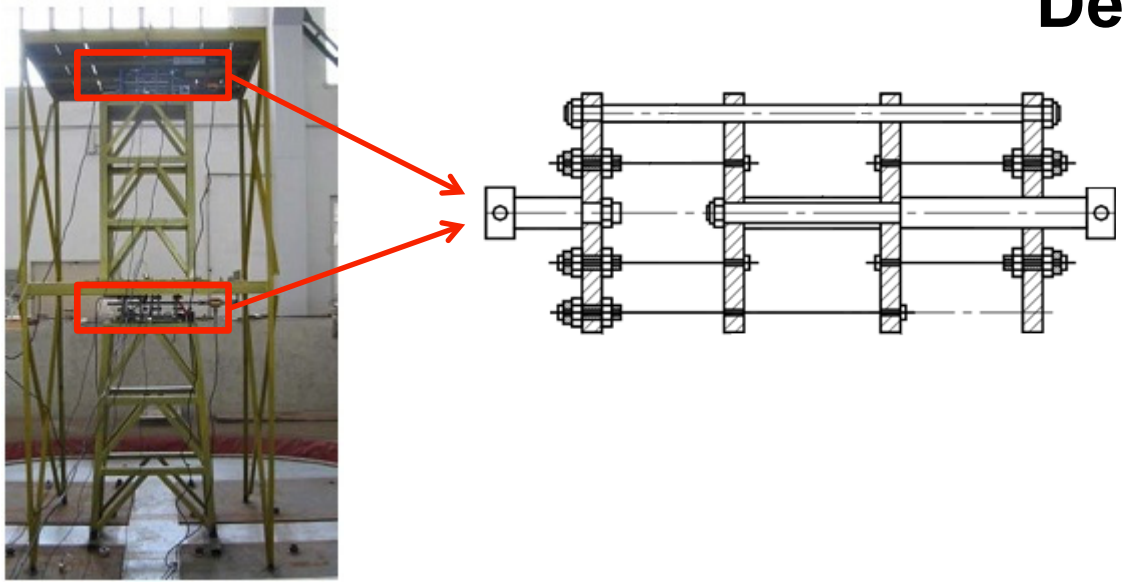


Recentering Damping Device (RDD)

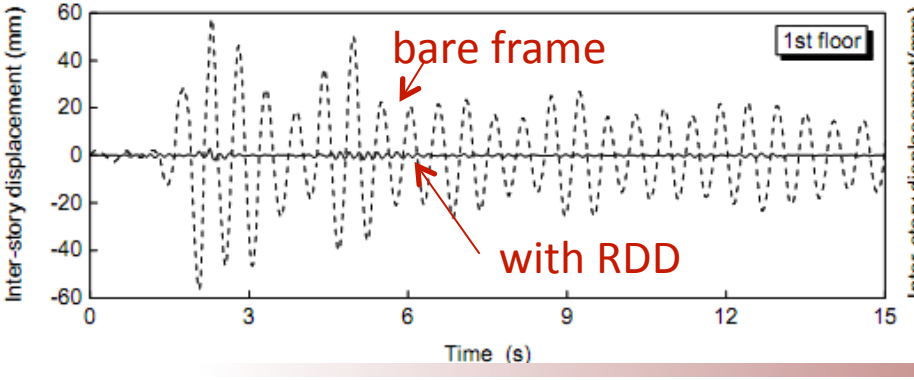


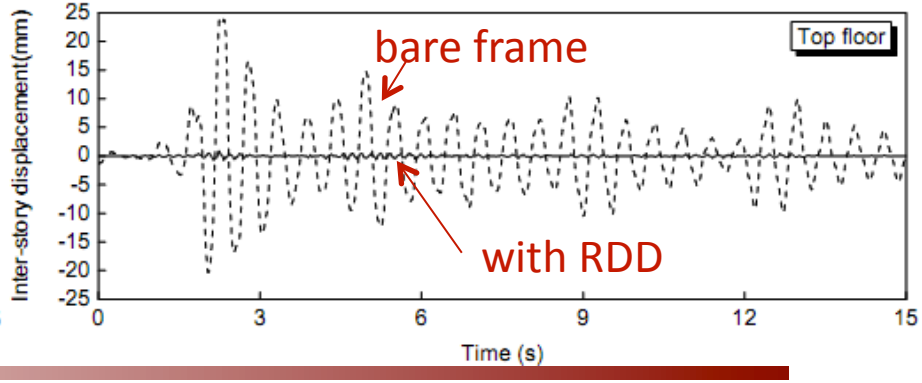
Shape Memory Alloys Applications

Shacking table tests



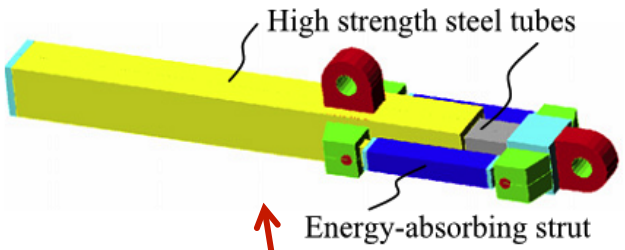
Recentering Damping Device: Example

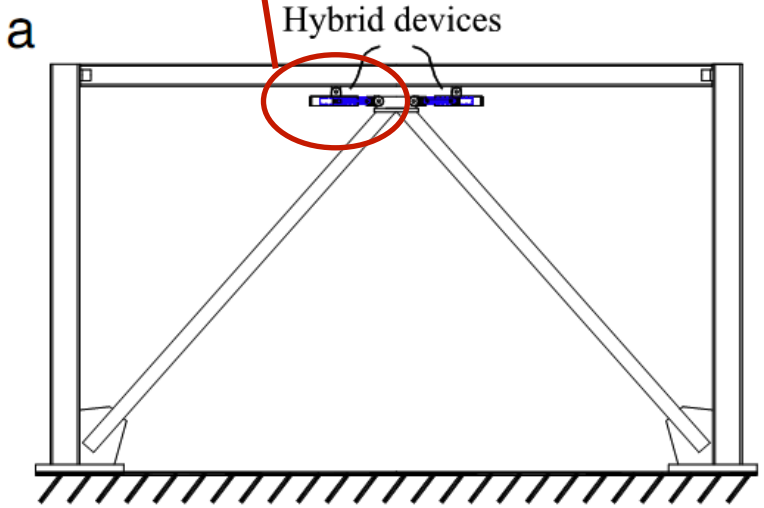


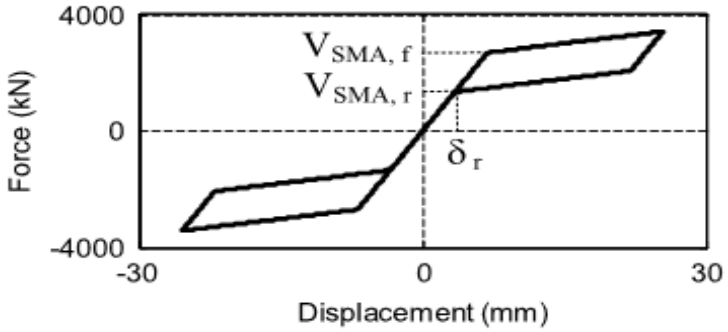


Shape Memory Alloys Applications

Hybrid device = **SMA device + energy absorption device**

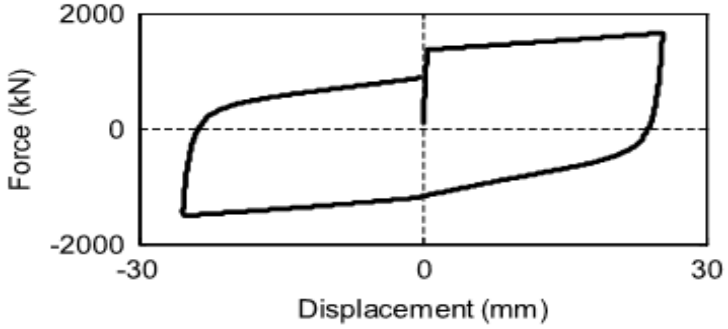






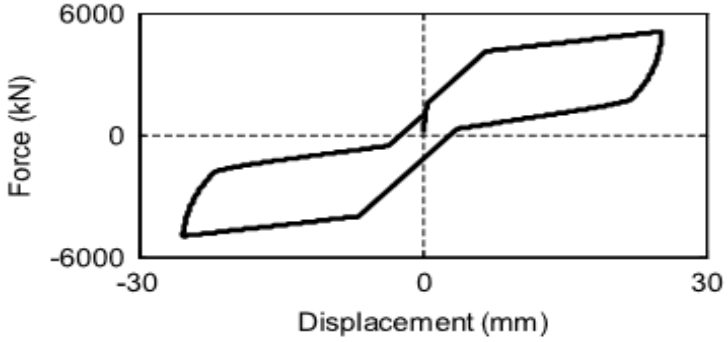
SMA wires

+



Strut

||



Hybrid device

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Shape-Memory Alloy Devices

fast loading rates ⟶ non-isothermal regime

slow loading rates ⟶ isothermal regime

$$
\begin{aligned}
\dot{x} &= v \\
\dot{v} &= -\left[x - \operatorname{sgn}(x)\,\lambda\xi\right] - 2\zeta v + \gamma\cos\Omega t \\
\dot{\xi} &= \frac{Z_1}{Z_1 Z_2 - 1}\left[J\operatorname{sgn}(x)\,v - h\left(\vartheta - \vartheta_E\right)\right] \\
\dot{\vartheta} &= \frac{1}{1 - Z_1 Z_2}\left[J\operatorname{sgn}(x)\,Z_1 Z_2 v - h\left(\vartheta - \vartheta_E\right)\right]
\end{aligned}
$$

Nondifferentiable vector field

$$
Z_1 = \frac{G}{1 + J\mu G}, \quad Z_2 = -L\left[J\left(|x| - \mu\xi\right) + \vartheta_0\right]
$$

$$
\hat{G} = \begin{cases} \hat{k}_1\left(1 - \xi\right)\left[1 + \tanh(\hat{k}_1 \Pi + \hat{k}_2)\right], & \text{if } \dot{\xi} > 0 \\ \hat{k}_3 \xi[1 - \tanh(\hat{k}_3 \Pi + \hat{k}_4)], & \text{if } \dot{\xi} < 0 \end{cases}
$$

Hysteresis operator

- W. Lacarbonara et al. (2004) Nonlinear thermomechanical oscillations of shape-memory devices. **Int J Solids Stru 41**.

Constitutive equations: free energy

Free energy function

$$\hat{\Phi} := \frac{K}{2}\left(x - sgn(x)\delta\xi\right)^2 + c\left(\vartheta - \vartheta_0 - \vartheta \ln\frac{\vartheta}{\vartheta_0}\right) + \left(\vartheta - \vartheta_0\right) b\,\delta\,\xi + a_0 - b_0\vartheta$$

elastic energy

chemical free energy

K elastic stiffness
δ max pseudoel. displ.
c specific heat
ϑ_0 reference temp. (fully Aust. state)
b tranf. force/temp. slope
a_0 internal energy at ref. temp.
b_0 entropy " "

$$f = K\left(x - sgn(x)\delta\xi\right)$$

$$\eta = c\ln\frac{\vartheta}{\vartheta_0} - b\,\delta\,\xi + b_0$$

$$\dot{\Gamma} = \left[K\left(|x|\delta - \delta^2\xi\right) + \left(\vartheta - \vartheta_0\right) b\,\delta\right]\dot{\xi}$$

Π = thermodyn. driving force

Constitutive equations: transformation kinetic

- transformation kinetic

$$\dot{\xi} = G\,\dot{\Pi}$$

- hysteresis operator G

$$G\left[|x|,\vartheta,\xi,sgn(\dot{\xi})\right] = \begin{cases} k_1(1-\xi)\left[1+\tanh k_1\left(k_1\Pi+k_2\right)\right] & \text{if} \quad \dot{\Pi}>0 \\ k_3\xi\left[1-\tanh k_1\left(k_3\Pi+k_4\right)\right] & \text{if} \quad \dot{\Pi}<0 \end{cases}$$

- Clausius-Duhem inequality $\dot{\Gamma} = \Pi\,\dot{\xi} = \Pi\,G\,\dot{\Pi} \geq 0$

- experimental data $\left(f_{Ms}, f_{Mf}\right)\left(f_{As}, f_{Af}\right) \Rightarrow \left(k_1,k_2,k_3,k_4\right)$

Path-following: finite-difference approach

Dynamical system: $\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, t; \boldsymbol{c}) \qquad \mathbf{f}: \ \mathbb{R}^n \times \mathbb{R} \times \mathbb{R}^m \longrightarrow \mathbb{R}^n$

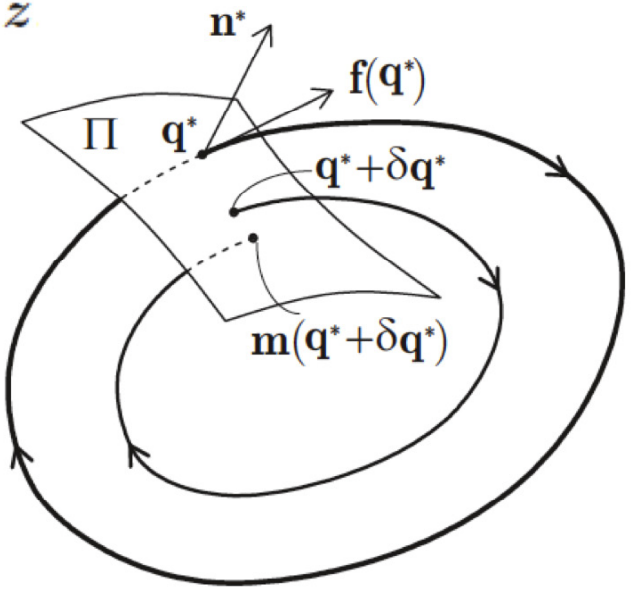
$(\mathbf{x}, t, \boldsymbol{c}) \in \mathbb{R}^n \times \mathbb{R} \times \mathbb{R}^m$: *state-control* space

Trajectories $\varphi(t; \mathbf{z}, \boldsymbol{c}) \qquad \mathbf{x}(0) = \mathbf{z}$

Periodic solutions $\varphi(T; \mathbf{z}^*, \boldsymbol{c}) = \mathbf{z}^*$

Poincarè map $\mathbf{m}(\mathbf{p}, \boldsymbol{c}) := \varphi(T_p; \mathbf{p}, \boldsymbol{c})$

Periodic solutions $\mathbf{m}(\mathbf{p}, \boldsymbol{c}) - \mathbf{p} = \mathbf{o}$



Monodromy matrix

$$\mathbf{M}(T; \mathbf{z}^*, \boldsymbol{c}) := \frac{\partial \varphi(T; \mathbf{z}^*, \boldsymbol{c})}{\partial \mathbf{z}} = \frac{\partial \mathbf{m}(\mathbf{q}^*, \boldsymbol{c})}{\partial \mathbf{p}}$$

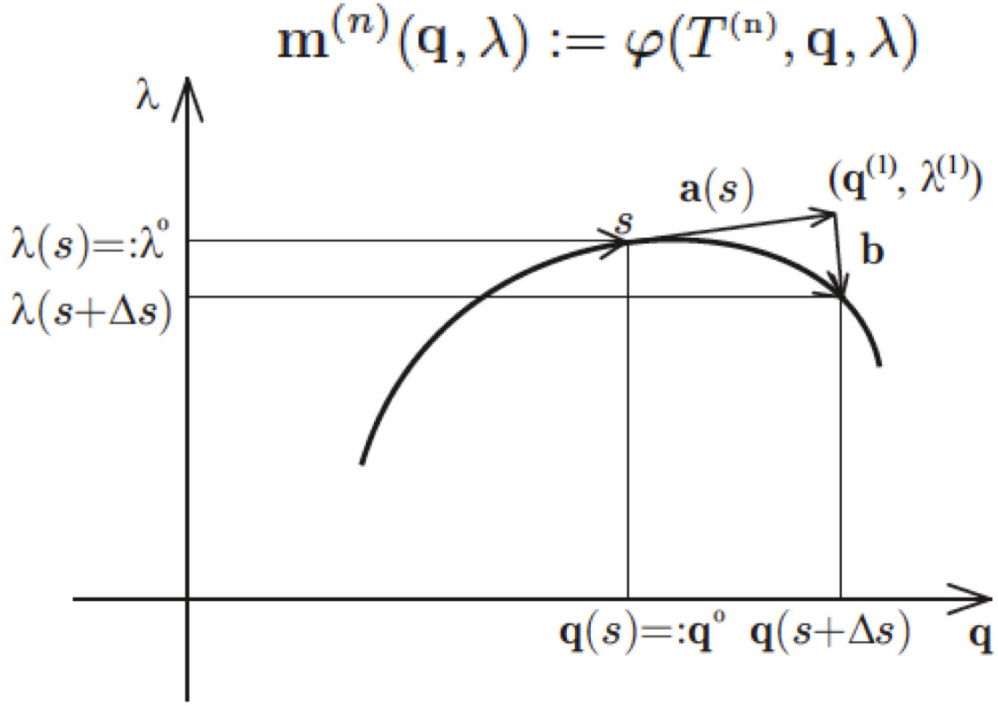
Path-following: finite-difference approach

Pseudo-arclength parametrization

Augmented system (n+1): Map+normality condition

Newton-Raphson scheme

Central finite differences:



$$\frac{\partial \mathbf{m}^{(n)}}{\partial p_j}(\mathbf{q}^*,\lambda) \approx \frac{\mathbf{m}^{(n)}(\mathbf{q}^* + \delta_1 \mathbf{e}_j, \lambda) - \mathbf{m}^{(n)}(\mathbf{q}^* - \delta_1 \mathbf{e}_j, \lambda)}{2\delta_1}$$

$$\frac{\partial \mathbf{m}^{(n)}}{\partial \lambda}(\mathbf{q}^*,\lambda) \approx \frac{\mathbf{m}^{(n)}(\mathbf{q}^*, \lambda + \delta_2) - \mathbf{m}^{(n)}(\mathbf{q}^*, \lambda - \delta_2)}{2\delta_2}$$

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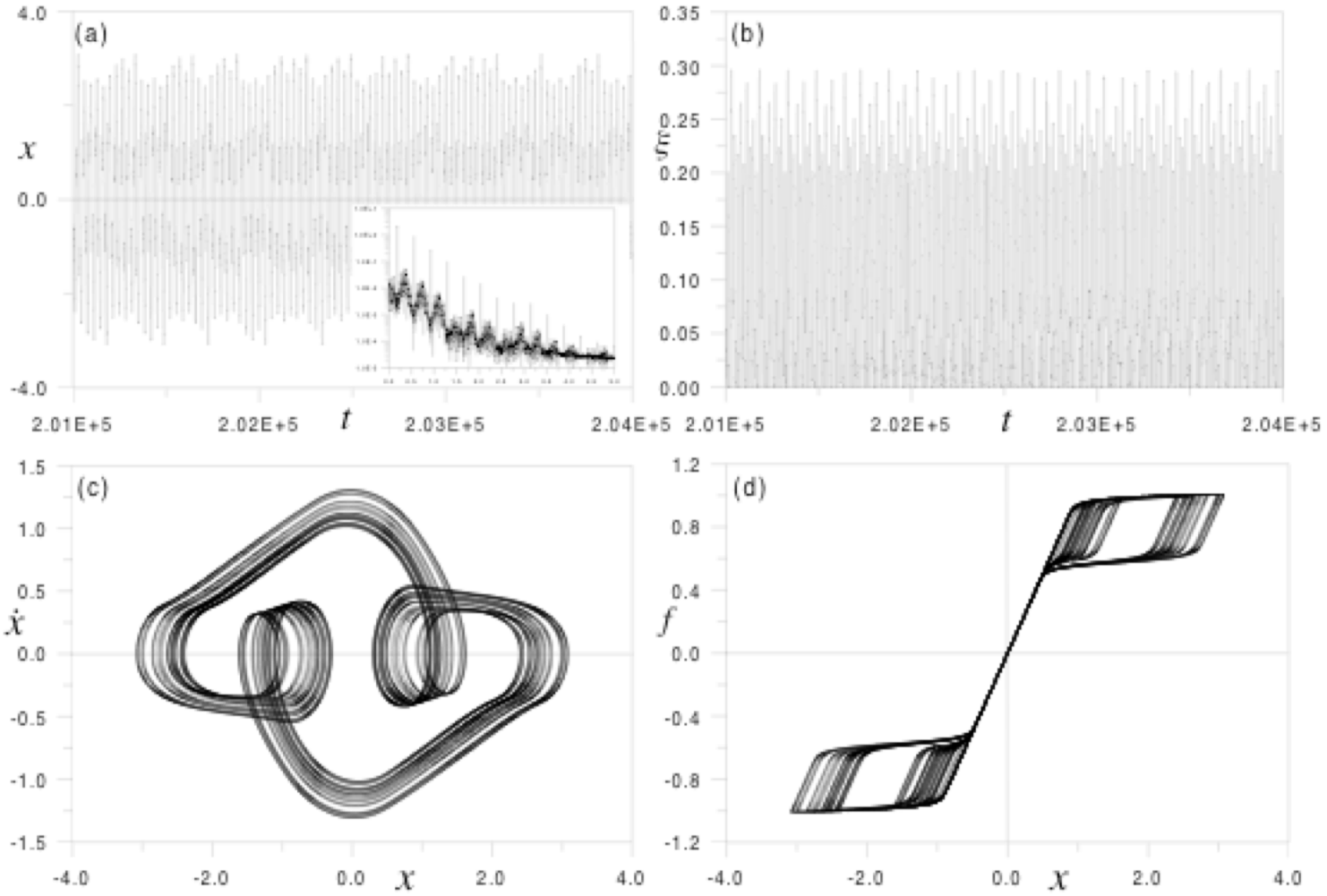
Shape-Memory Alloy Devices

Shape Memory Alloys: isothermal phase transformations



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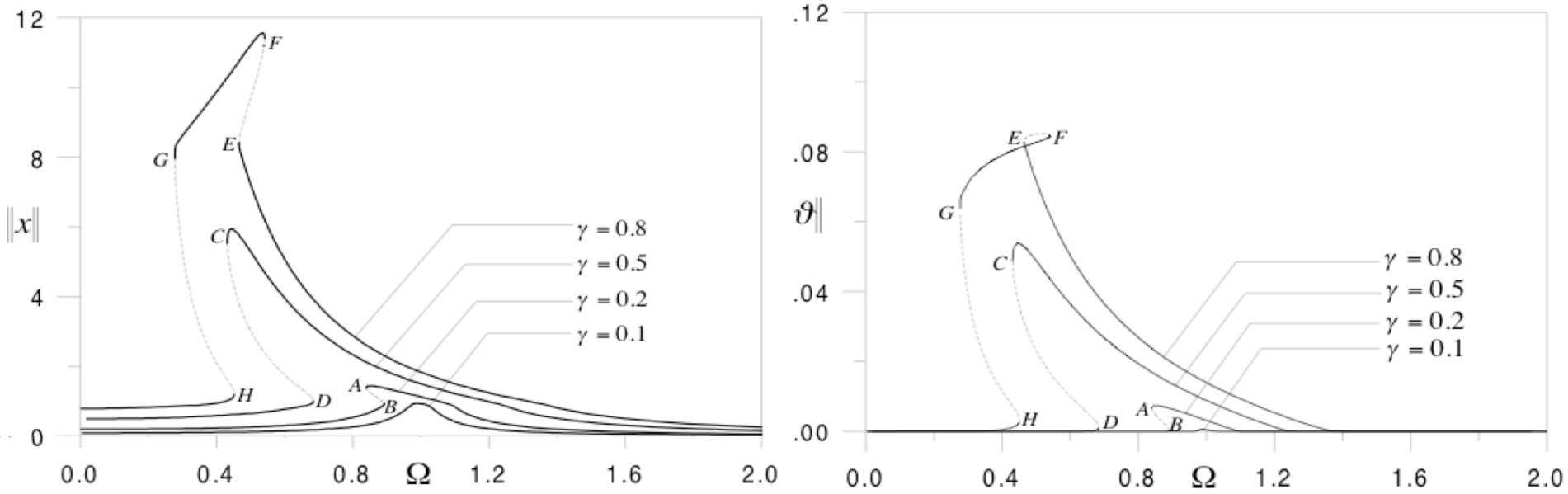
Shape-Memory Alloy Devices

Shape Memory Alloys: non-isothermal phase transformations

non-adiabatic conditions



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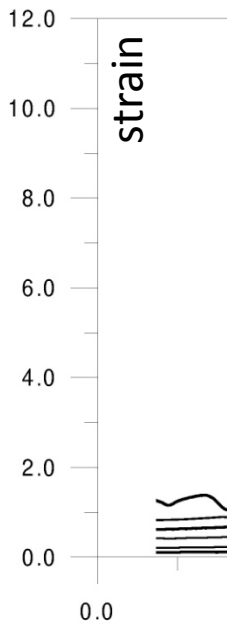
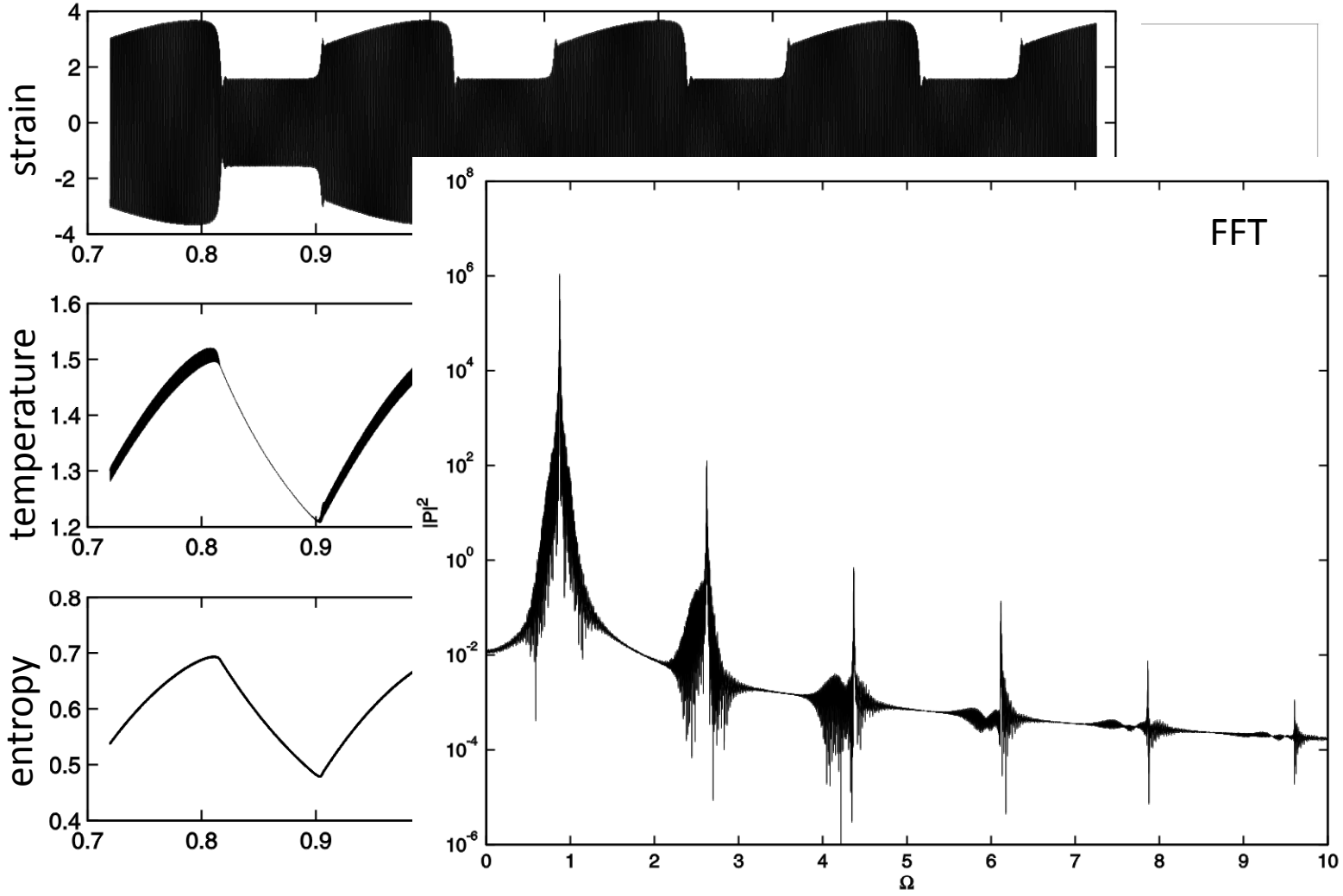
Shape-Memory Alloy Devices

Shape Memory Alloys: non-isothermal phase transformations nearly adiabatic conditions





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Future directions

SMA Wires for TMDs

- nonlinear model for SMA wires under flexure with inter-strand friction

Computational approach

- path-following for TMD optimization, best compromise between pseudoelastic dissipationa and interstrand friction
- design methodology

Experiments

- cyclic loading tests and identifaction
- frequency-response curves of SMA TMD mounted on a 1 dof structure
- fatigue testing, temperature effects