L'utilizzo della dinamica sperimentale per la diagnostica e il monitoraggio delle strutture

WEBINAR – 5 dicembre 2022

La dinamica sperimentale per il monitoraggio

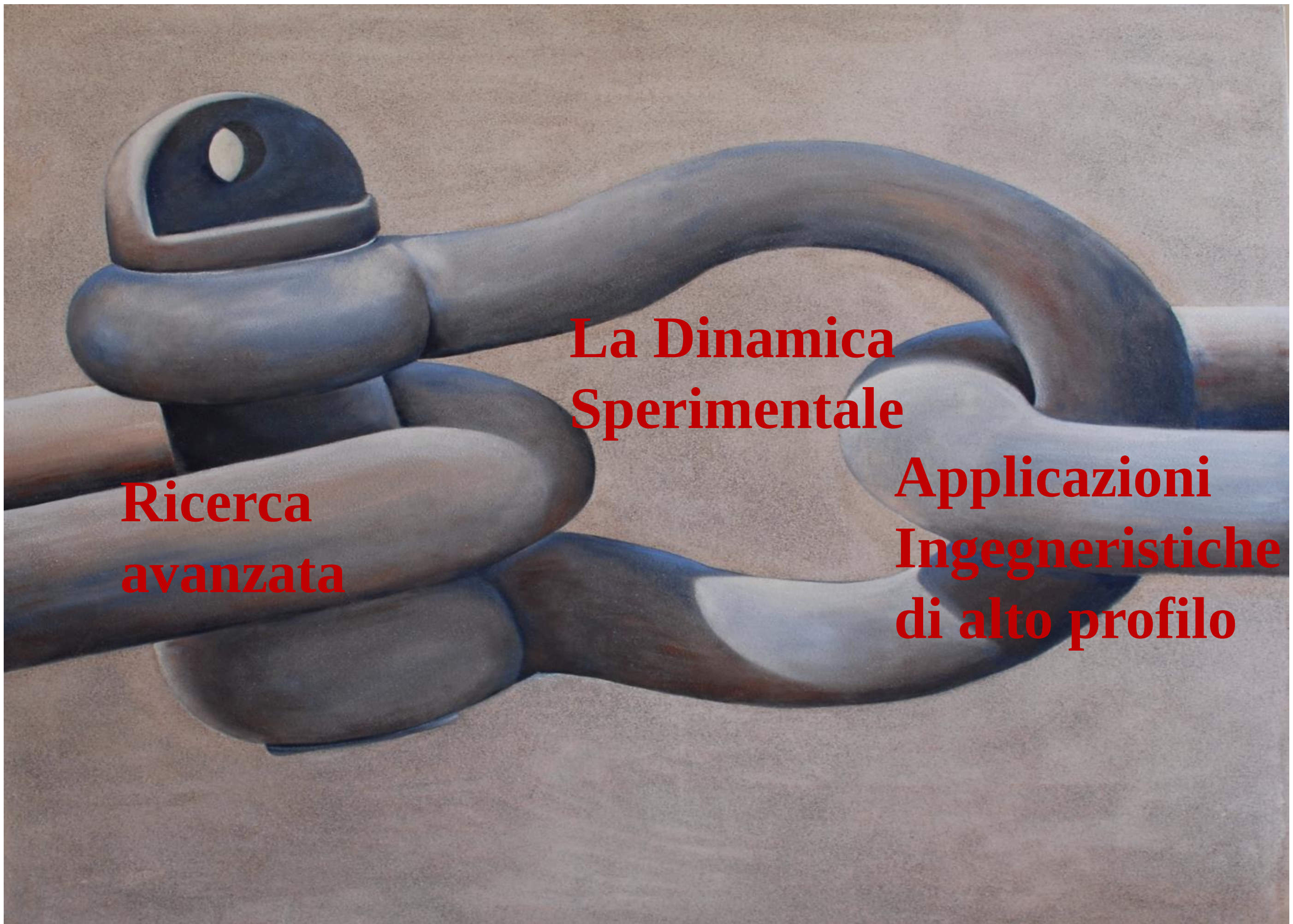
Antonina Pirrotta
Università degli Studi di Palermo
Presidente IDEA

Innovative Dynamics Experiments Association (IDEA)

- **Gianni BARTOLI**, Università di Firenze
- **Luigi CARASSALE**, Università di Genova
- **Giovanni FABBROCINO,** Università del Molise
- **Carmelo GENTILE**, Politecnico di Milano
- **Massimiliano GIOFFRÈ**, Università di Perugia
- **Giacomo Camillo NAVARRA**, Università Kore di Enna
- **Antonina PIRROTTA**, Università di Palermo
- **Walter SALVATORE,** Università di Pisa
- **Filippo UBERTINI,** Università di Perugia

La Dinamica Sperimentale

cuore pulsante dell'Ingegnere

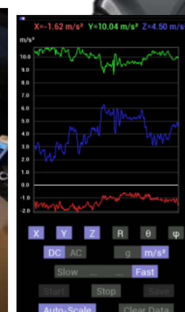


Monitoraggio

Monitoraggio

Steri di Palermo (Rettorato)

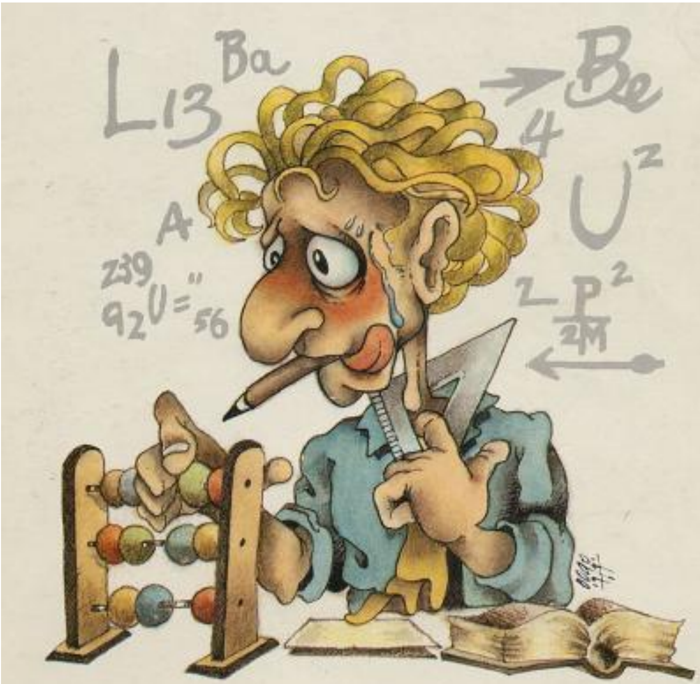
Radar



CROWDSENSE

Experimental Dynamics, Monitoring and BIM (Materia a scelta)

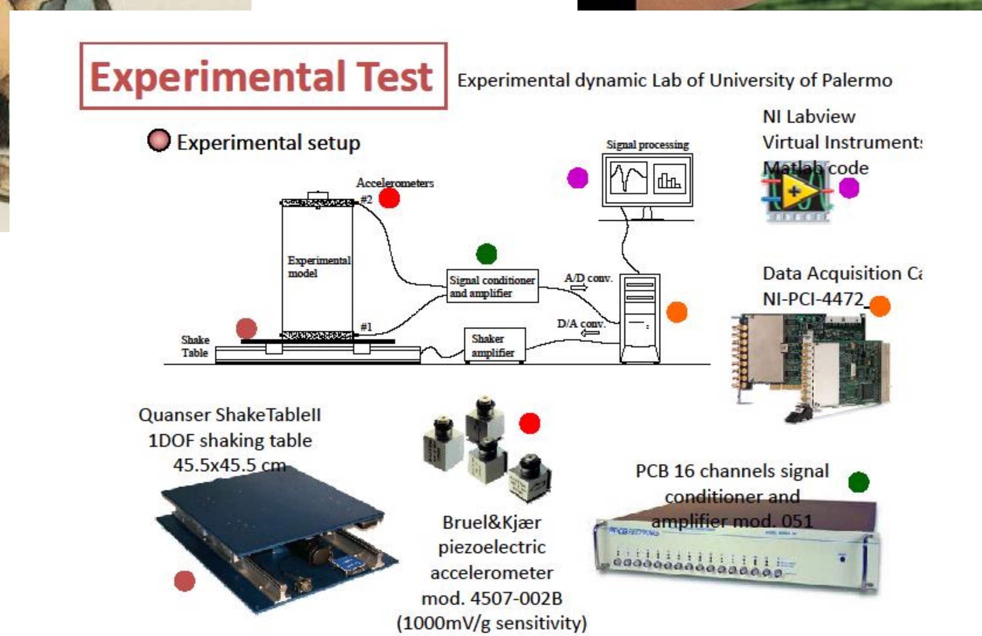
Mathematics



Reality

Mathematics

Reality



Scientific Method Components

Characterizations (observations)

Hypotheses (theoretical)

Predictions (reasoning)

Experiments

Galileo Galilei
Pisa, 15 febbraio 1564 –
Arcetri, 8 gennaio 1642

Scientific Method Components

Characterizations (observations)

Hypotheses (theoretical)

Predictions (reasoning)

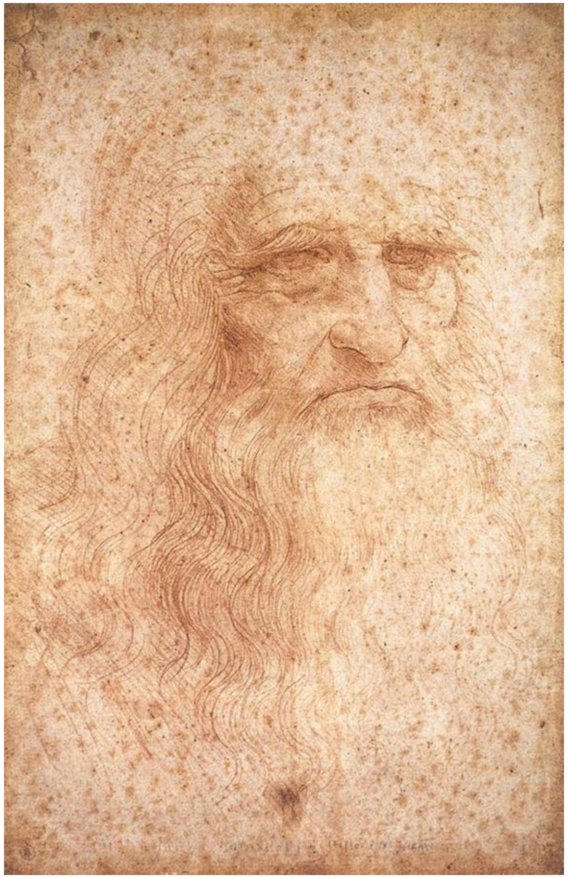
Experiments ★

VIRTUAL EXPERIMENT

Efficient Experiments allow to build up virtual experiments

Once a proposed theoretical formulation is reliable
having confirmed efficient tests

Simulations from this Mathematical formulation
are
virtual experiments



Those who fall in love with practice without science are like the helmsman, who enters a ship without a rudder or compass, who is never sure where to go.

Quelli che s’innamoran di pratica sanza scienzia son come ‘l nocchier ch’entra in navilio senza timone o bussola, che mai ha certezza dove si vada. Sempre la pratica deve essere edificata sopra la bona teorica.

It doesn’t matter how beautiful your theory is,
it doesn’t matter how smart you are.
If it doesn’t agree with experiment, it’s wrong

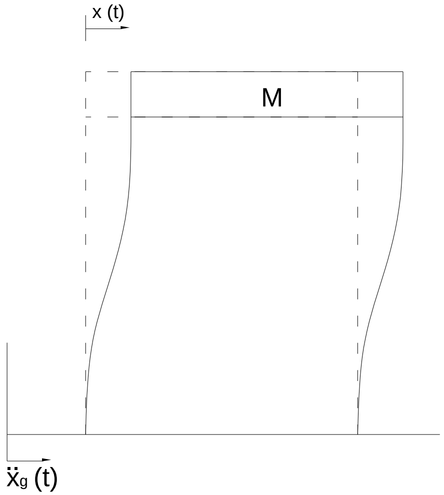
Non importa quanto sia bella la tua teoria, non importa quanto tu sia intelligente. Se non concorda con l'esperimento, è sbagliata.

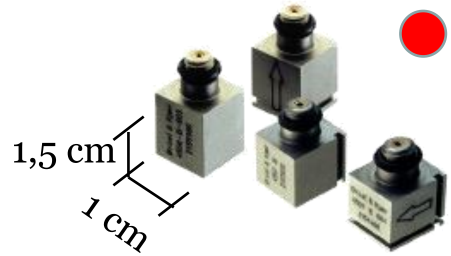
Leonardo Da Vinci

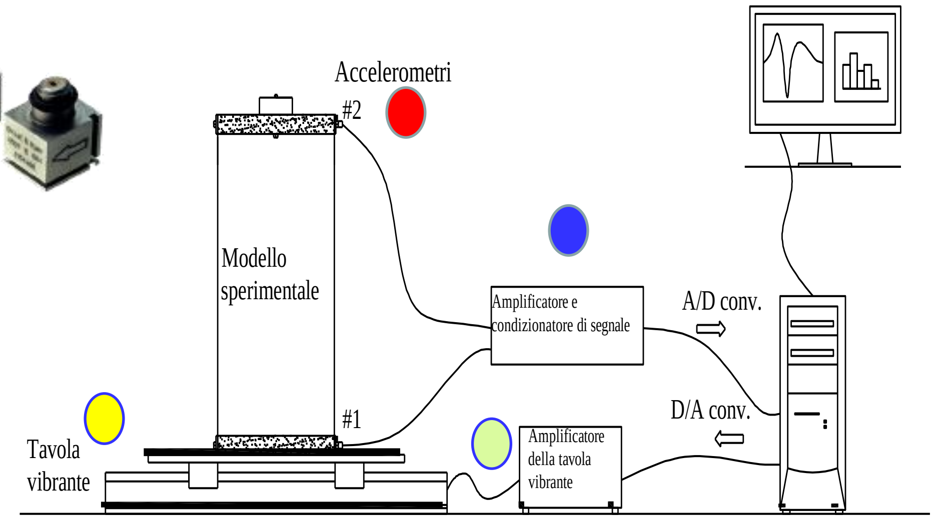
Anchiano, 15 april 1452
– Amboise, 2 may 1519

Richard Phillips Feynman
11 May 1918 New York
15 february 1988 Los Angeles

Setup sperimentale







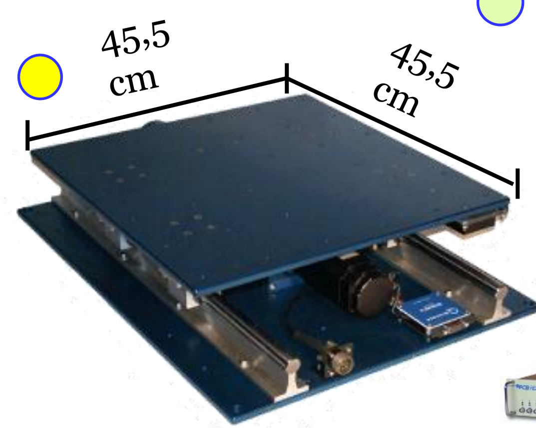
Modellazione matematica: il sistema non controllato (SDOF)

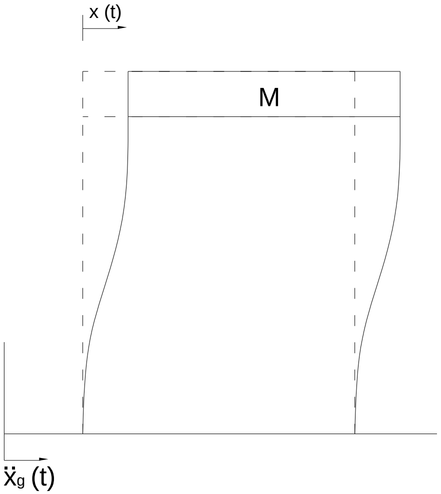
$$M\ddot{x} + C\dot{x} + Kx = -M\ddot{x}_g$$

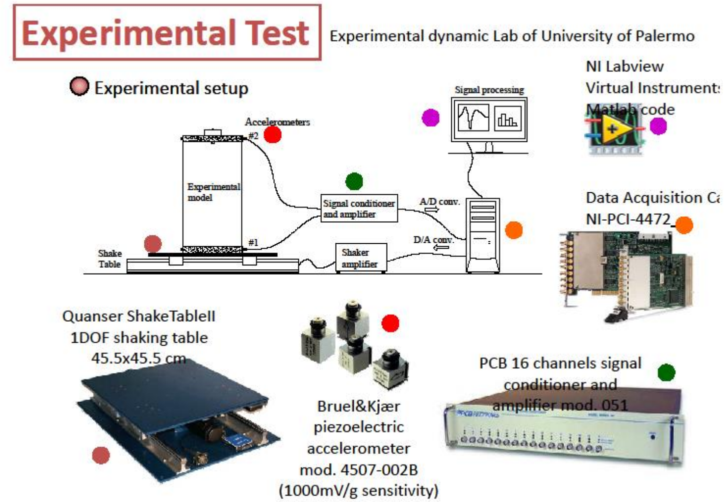
$M = 4.503 kg;$

$C = 0.253 Ns/m;$

$K = 451.78 N/m$







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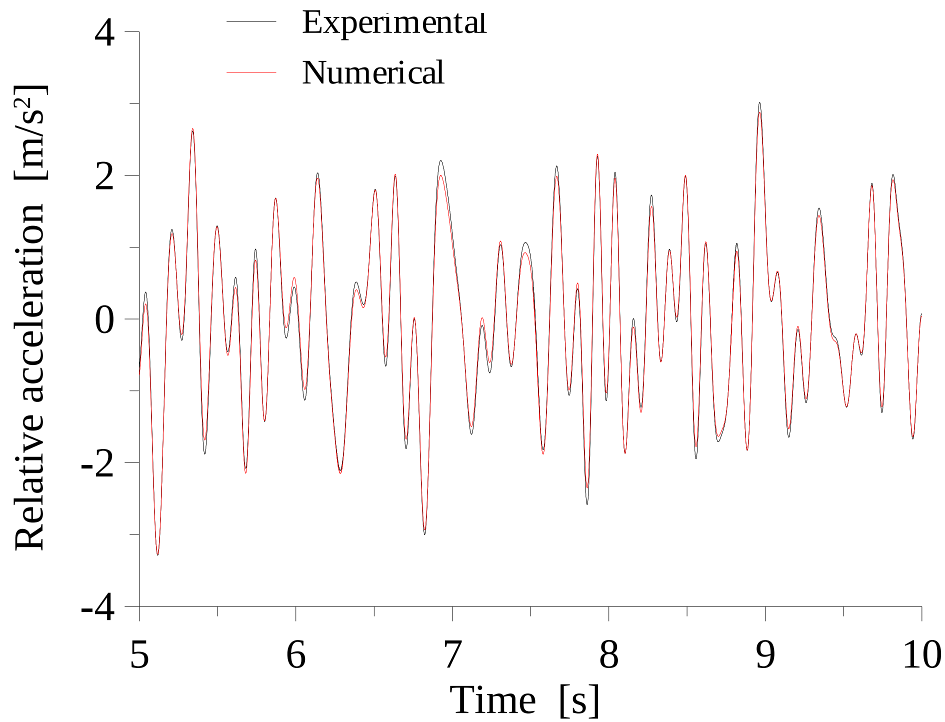
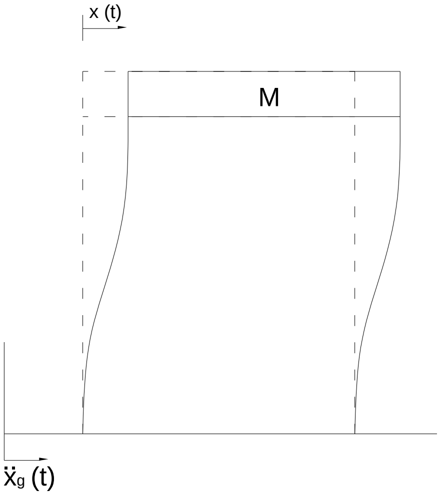
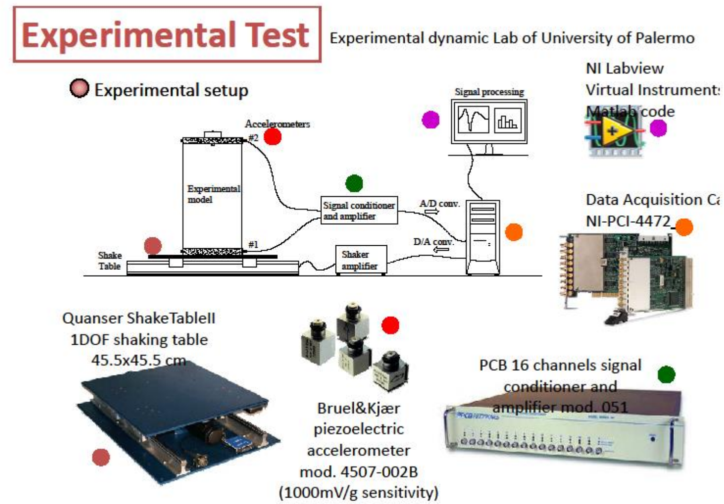


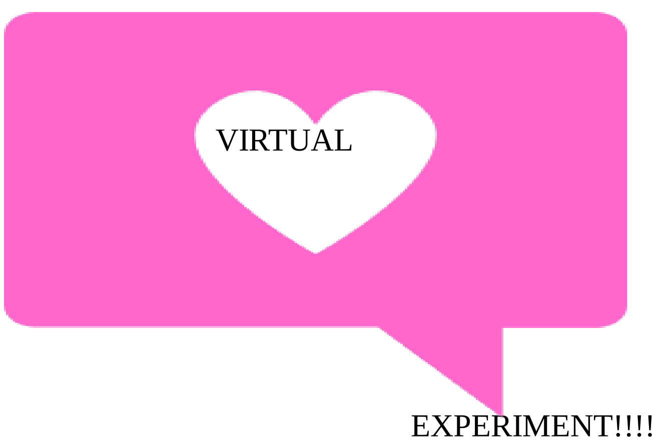
Setup sperimentale

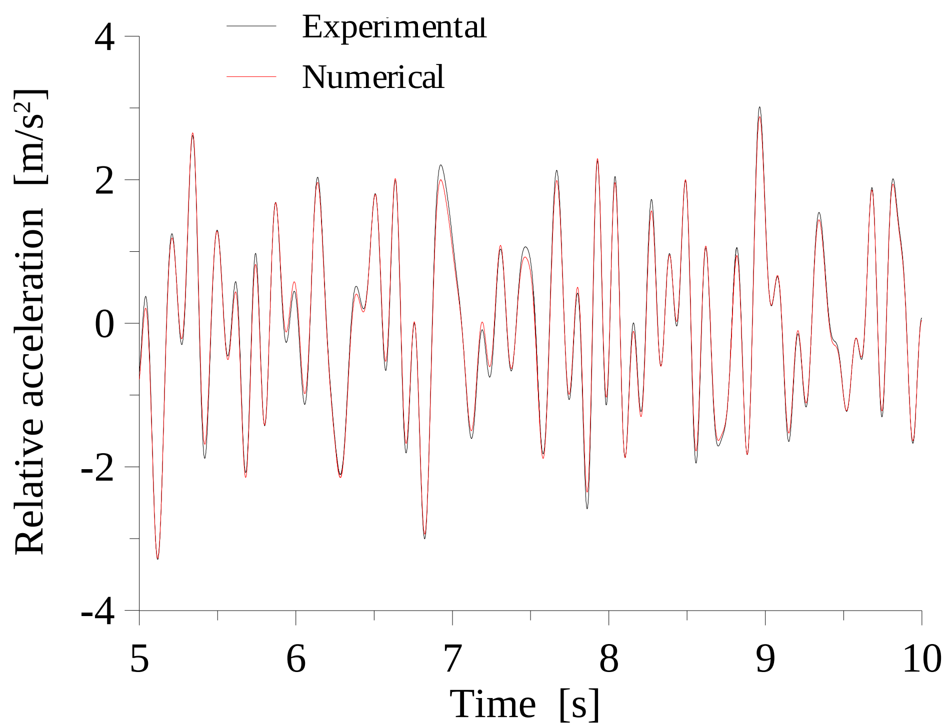




Mathematical model

$$M\ddot{x} + C\dot{x} + Kx = -M\ddot{x}_g$$



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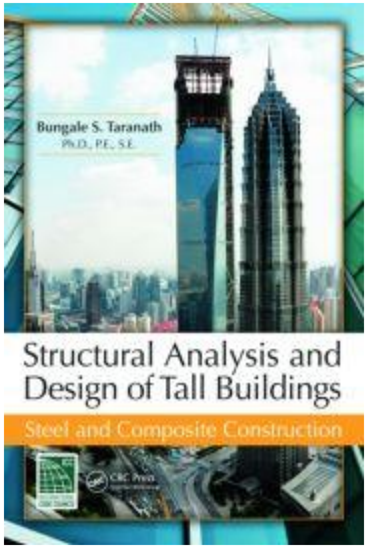
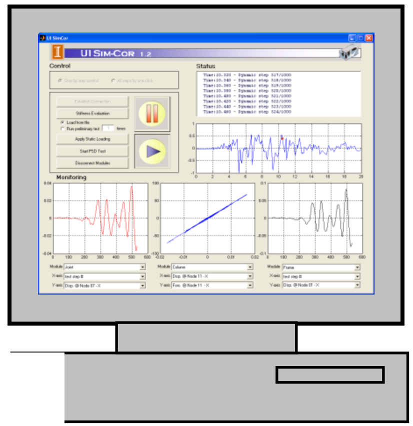
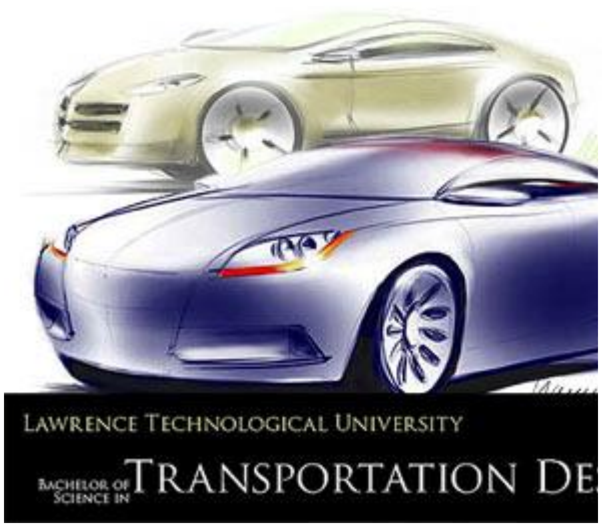
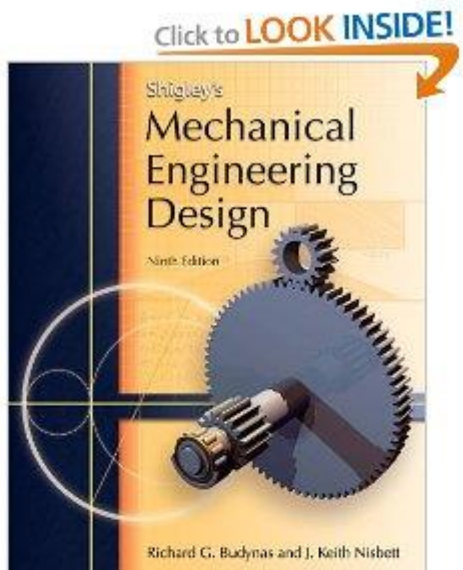
the most challenging problem

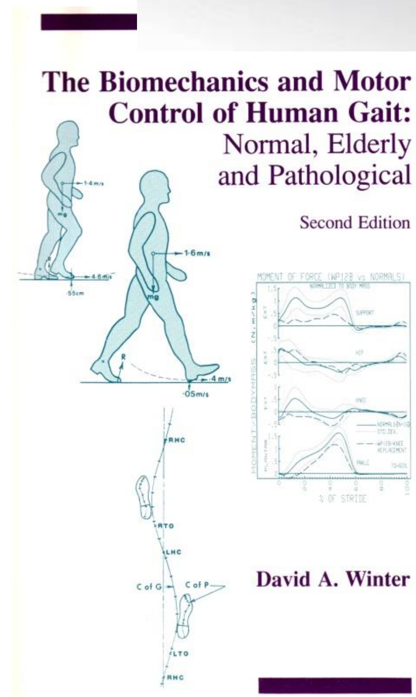
Virtual Experiments





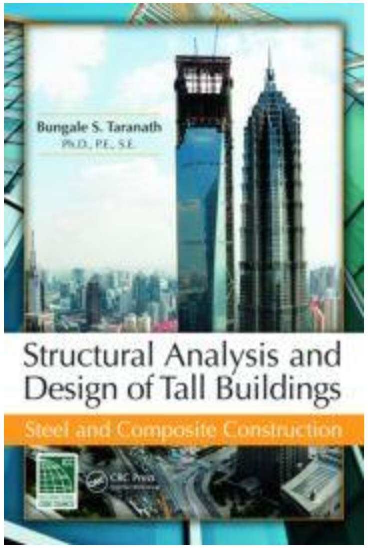


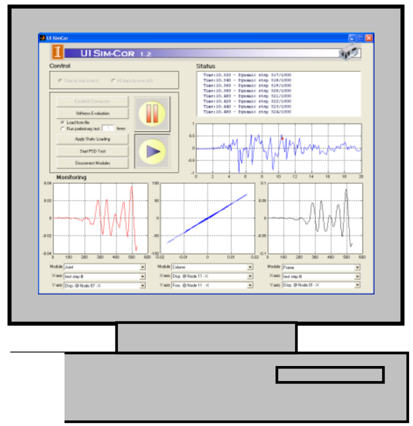


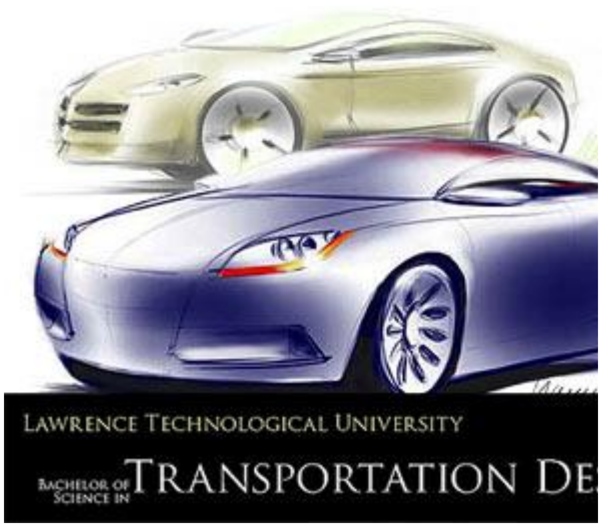


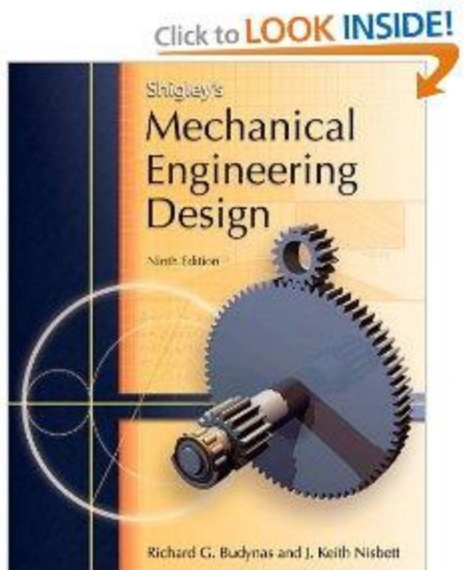
the most challenging problem

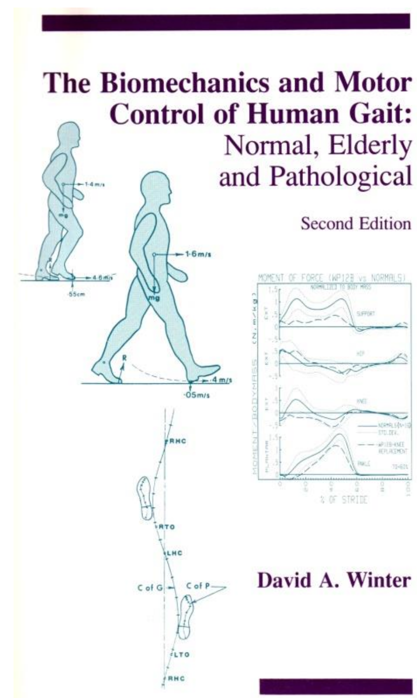
Virtual Experiments











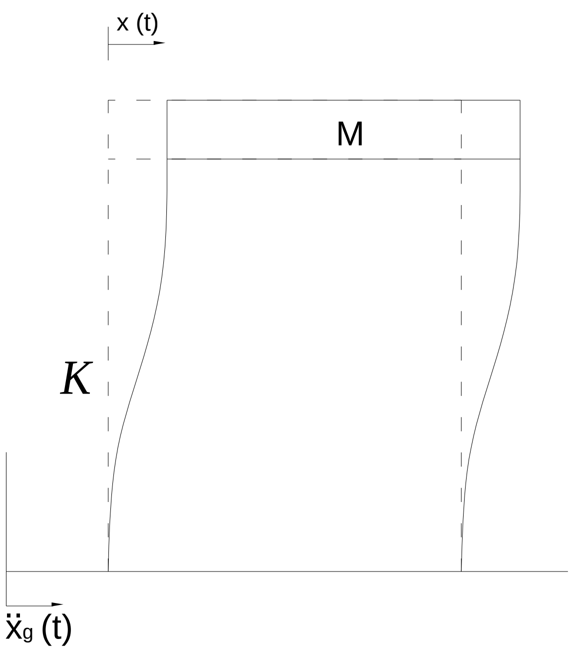
Passive control systems

A device is attached to a main system reducing vibration without external power supply

Ref.:
J.P.Den Hartog, 1928 "Mechanical vibration", McGraw-Hill, New York

Tuned Mass Damper (TMD) ⇨ *Mass-spring-dashpot connected to the main system*

Main system



$$M\ddot{x}+C\dot{x}+Kx=-M\ddot{x}_g$$

TMD controlled system

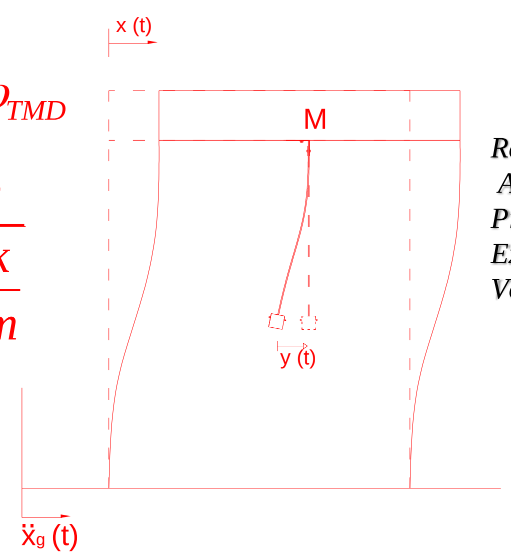
$$m_{TMD}=m$$

$$c=2m\zeta_2\omega_{TMD}$$

$$k=m\omega_{TMD}^2$$

$$\omega_{TMD}=\sqrt{\frac{k}{m}}$$

$$\boxed{\omega_1\cong\omega_{TMD}}$$



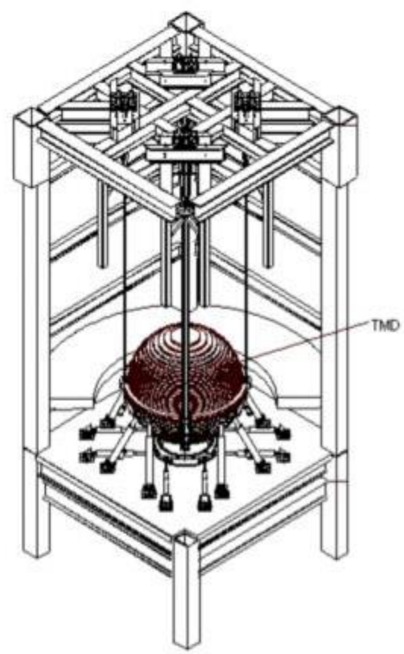
Ref.:
Adam C., Heuer R., Pirrotta A., 2003, Experimental Mechanics, Vol. 43(2), 124-130

$$\begin{cases} M\ddot{x}+(C+c)\dot{x}-c\dot{y}+(K+k)x-ky=-M\ddot{x}_g \\ m\ddot{y}-c\dot{x}+c\dot{y}-k\dot{x}+ky=-m\ddot{x}_g \end{cases}$$

Passive control systems

Tuned Mass Damper (TMD)

Taipei 101 (Taiwan):
Height: 448 m; TMD mass: 660 t



Passive control systems

- **Tuned Mass Damper (TMD)**

Hancock Tower (Boston):
Height: *277* m;
two TMDs of 300 t

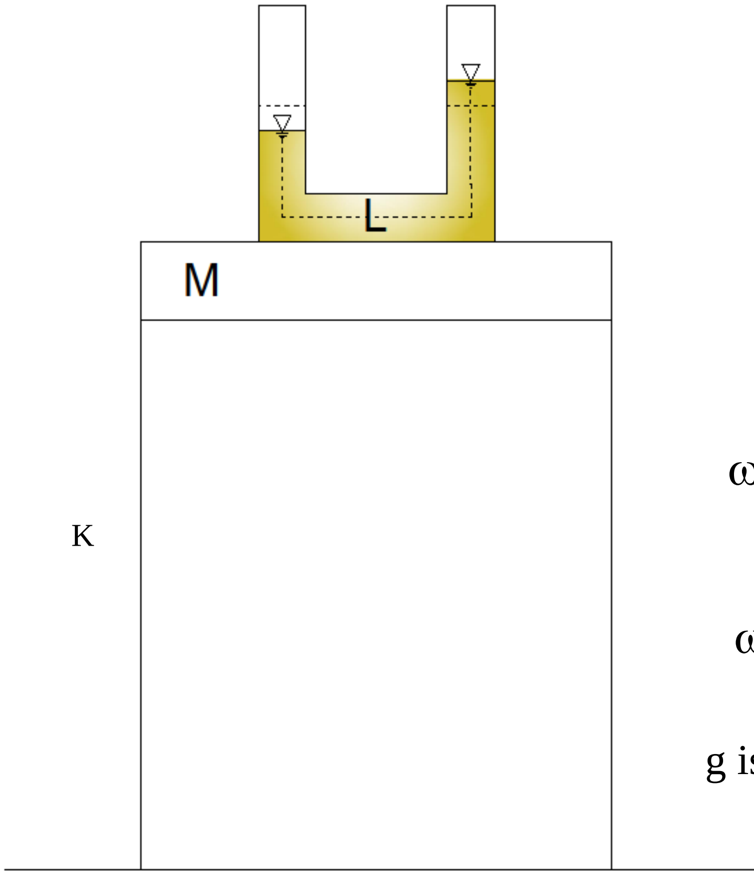
Citicorp Building (New York):
Height: *278* m; TMD mass: 410 t

Passive control systems

Tuned Liquid Column Damper (TLCD)

Replaces the mass-spring-dashpot By a U-tube-like container where the motion of a liquid column absorbs part of vibration

Ref. F. Sakai, S. Takeda, T. Tamaki, 1989",
Proc. of Intern. Conf. on highrise buildings, Nanjing, China



- ***Impart indirect damping effect to the primary structure through liquid oscillations***

$$\omega_1 = \sqrt{\frac{K}{M}};$$

$$\omega_2 = \sqrt{\frac{2g}{L}};$$

- ***The U-shaped tank is configured to have the natural frequency that optimally matches one or more of the structure's natural frequencies.***

g is the gravitational constant

$$\omega_1 \cong \omega_2$$

Classical analytical formulation

*Ref. T. Balendra, C.M. Wang, H.F. Cheong, 1995 Engineering Structures, **17**(9), 668-675*

Ref.: Hochrainer M. J., Ziegler F., 2006, Control of tall building vibrations by sealed tuned liquid column dampers, Structural Control and Health Monitoring, Vol. 13, 980–1002

$$\begin{cases} \left(M + m_{TLCD}\right)\ddot{x} + m_h \ddot{y} + C\dot{x} + Kx = -\left(M + m_{TLCD}\right)\ddot{x}_g \\ m_h \ddot{x} + m_{TLCD}\ddot{y} + \frac{1}{2}\rho A \xi \left|\dot{y}\right| \dot{y} + 2\rho A g y = -m_h \ddot{x}_g \end{cases}$$

Nonlinear term

M, C, K Mass, Damping and Stiffness of the main system

$$m_{TLCD} = \rho A\left(L_h + 2L_v\right) = \rho A L$$

$$m_h = \rho A L_h$$

x *Frame displacements*

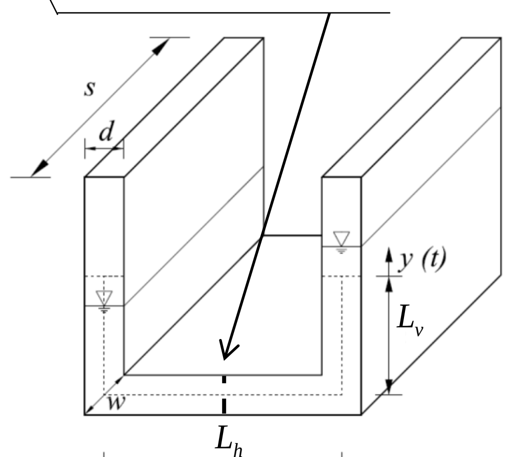
y *Vertical liquid displacement*

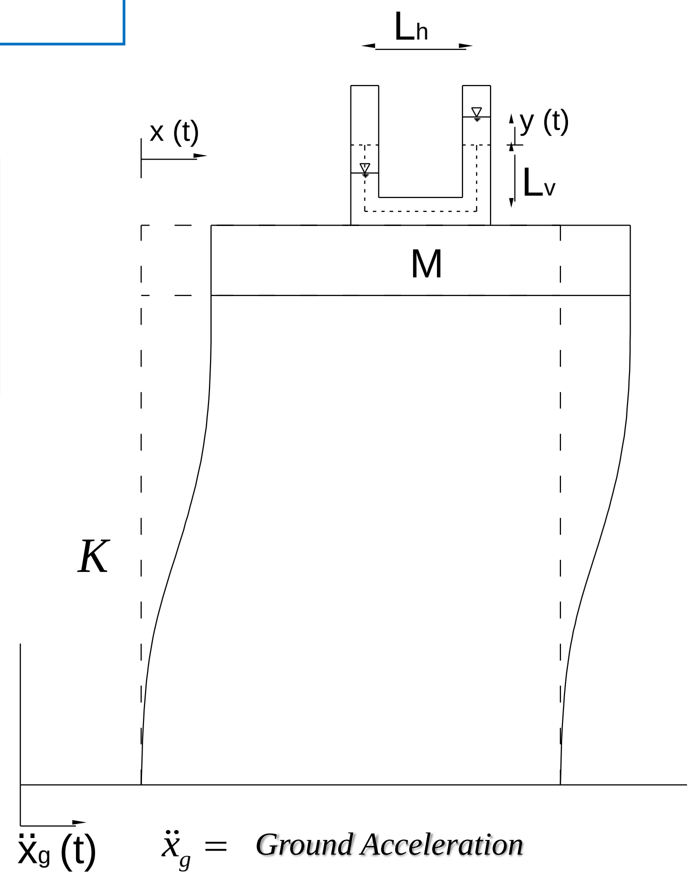
ρ *Density of the liquid inside the TLCD*

ξ *Head loss coefficient*

g *Gravity acceleration*

A *Tube cross section*





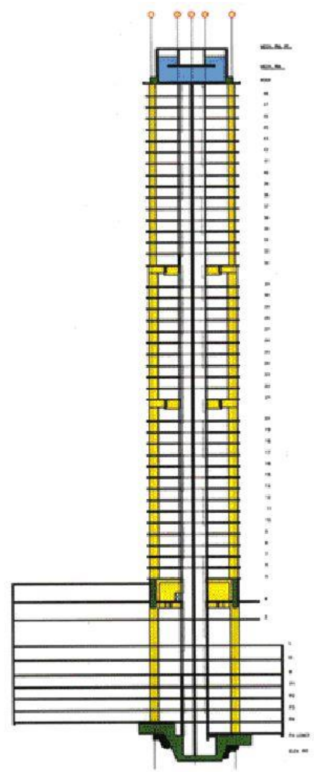
$\ddot{x}_g$ = *Ground Acceleration*

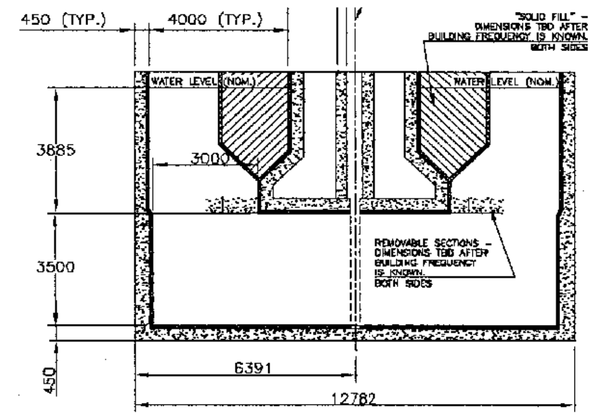
Tuning: $\omega_1 \cong \omega_2$ $\omega_1 = \sqrt{\frac{K}{M}}$; $\omega_2 = \sqrt{\frac{2g}{L_h + 2L_v}}$;

Passive control systems

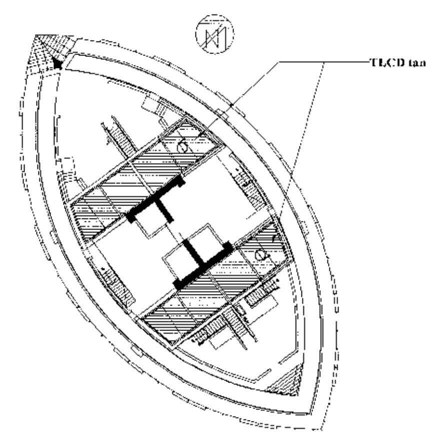
- **Tuned Liquid Column Damper (TLCD)**

One Wall Center (Vancouver):
Height: *149.8* m; two TLCDs of 230 t





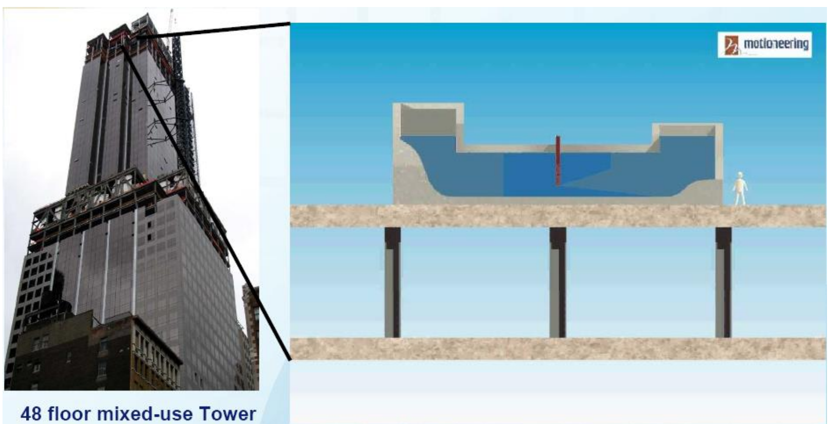
Tuned Liquid Column Damper of the One Wall Center

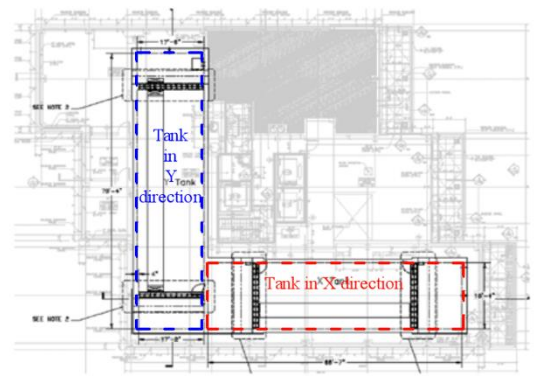


Passive control systems

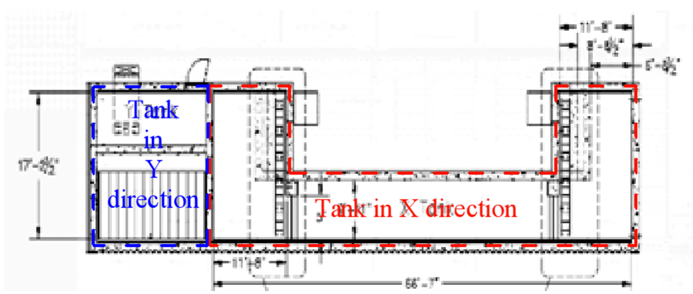
- **Tuned Liquid Column Damper (TLCD)**

Random House (New York):
Height: *208* m; two TLCDs of 430 and 290 t

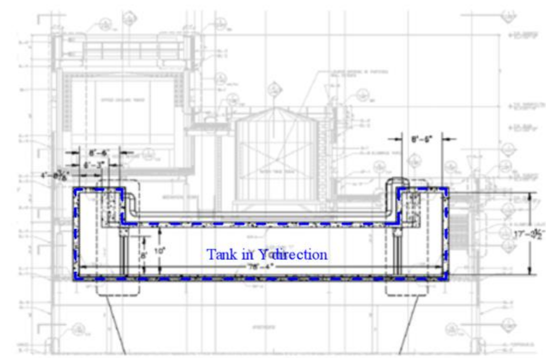




Random House 50° floor



East-West view of the Random House last floor



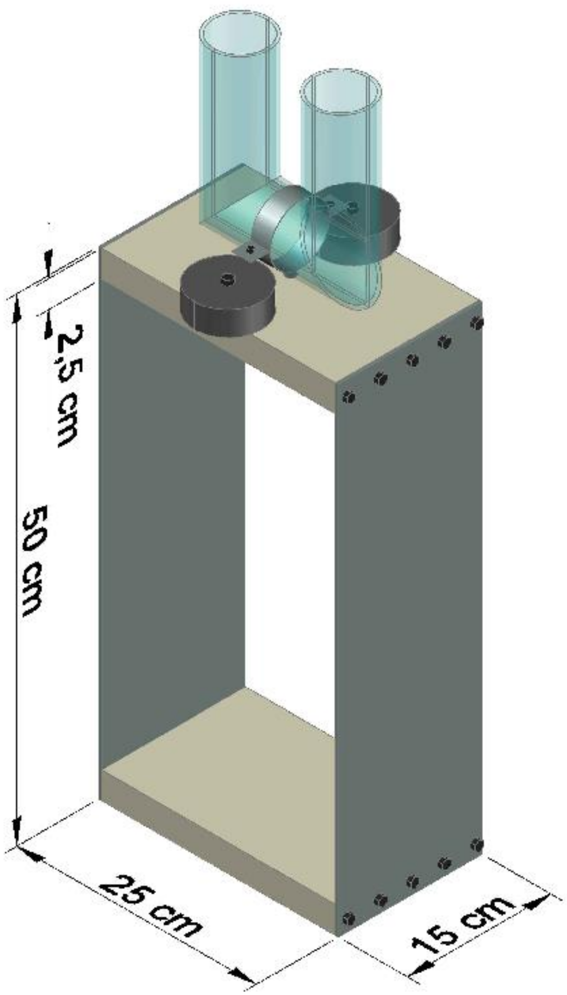
North-South view of the Random House last floor

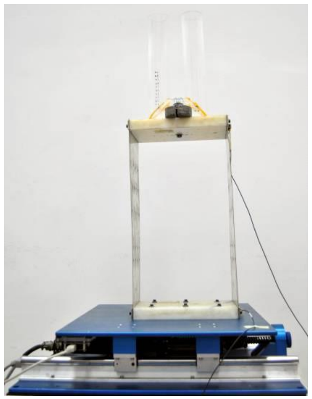
- Effectiveness of the control

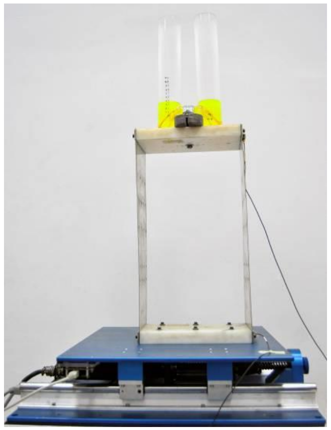
EFFECTIVENESS OF THE CONTROL

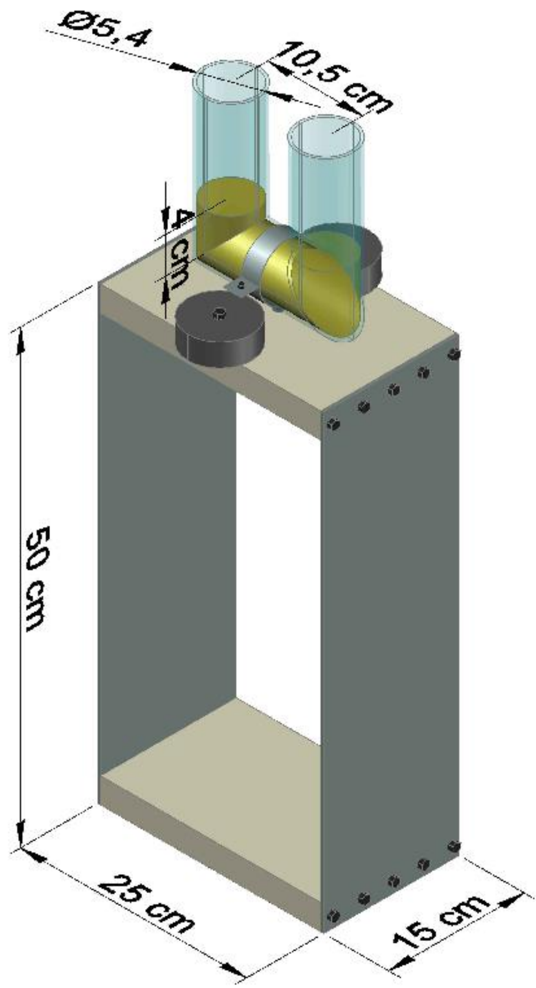
Experimental dynamic Lab of University of Palermo

- Uncontrolled system: main system (no liquid inside)
- TLCD controlled system









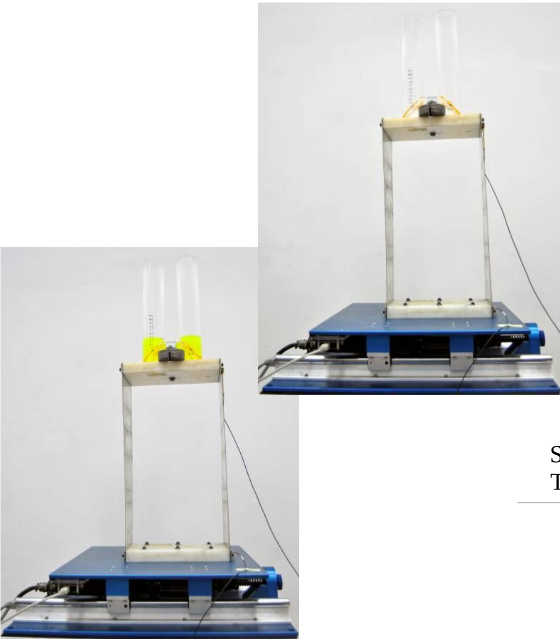
Experimental tests

Effectiveness of the control

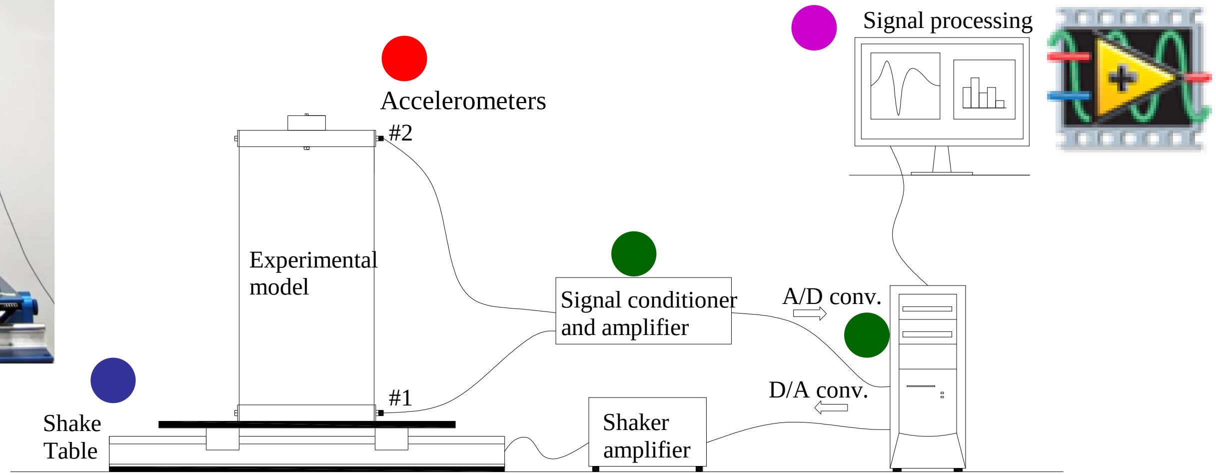
Experimental validation

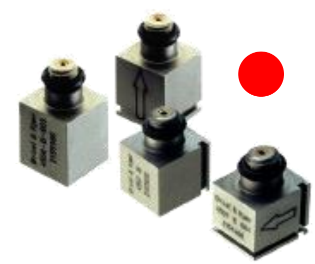
Experimental dynamic Lab of University of Palermo

Experimental setup



NI Labview
Virtual Instruments
Matlab code





National Instruments PXIe-1082 DAQ system

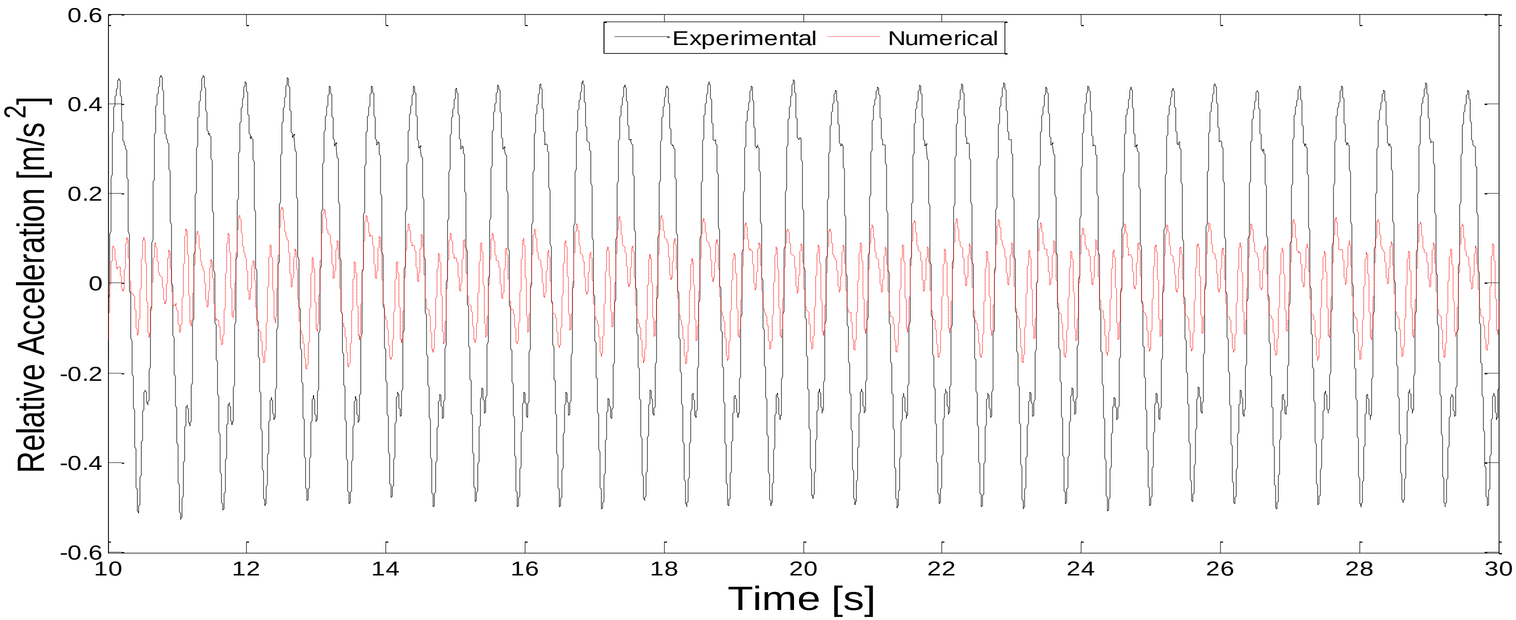
Quanser ShakeTableII
1DOF shaking table
45.5x45.5 cm

Bruel&Kjær piezoelectric
accelerometer
mod. 4507-002B
(1000mV/g sensitivity)

Numerical Vs Experimental results

$$\begin{cases} (M + m_{TLCD})\ddot{x} + m_h\ddot{y} + C\dot{x} + Kx = -(M + m_{TLCD})\ddot{x}_g \\ m_h\ddot{x} + m_{TLCD}\ddot{y} + \frac{1}{2}\rho A\xi|\dot{y}|\dot{y} + 2\rho Agy = -m_h\ddot{x}_g \end{cases}$$

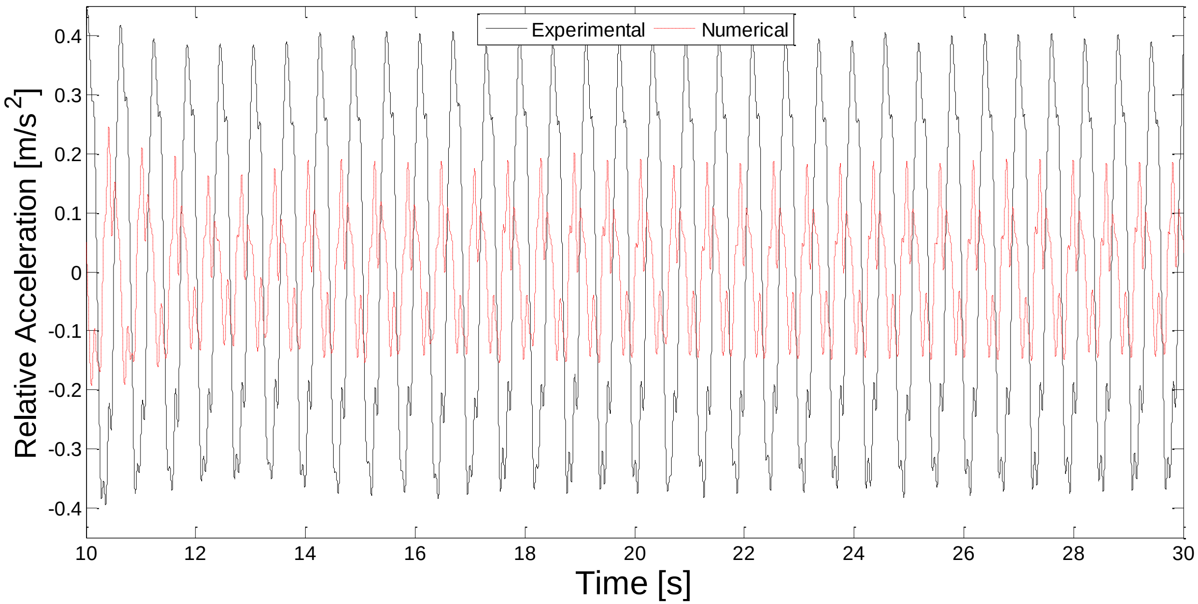
	Main Structures (uncontrolled system)	Controlled system
M [kg]	4.45027	4.45027
C [Ns/m]	0.7	0.7
K [N/m]	489.71	489.71
ξ		2
A [cm²]		22.9
L_h *[cm]*		10.5



Sinusoidal test: f=1.65Hz
(resonance of the uncontrolled system)

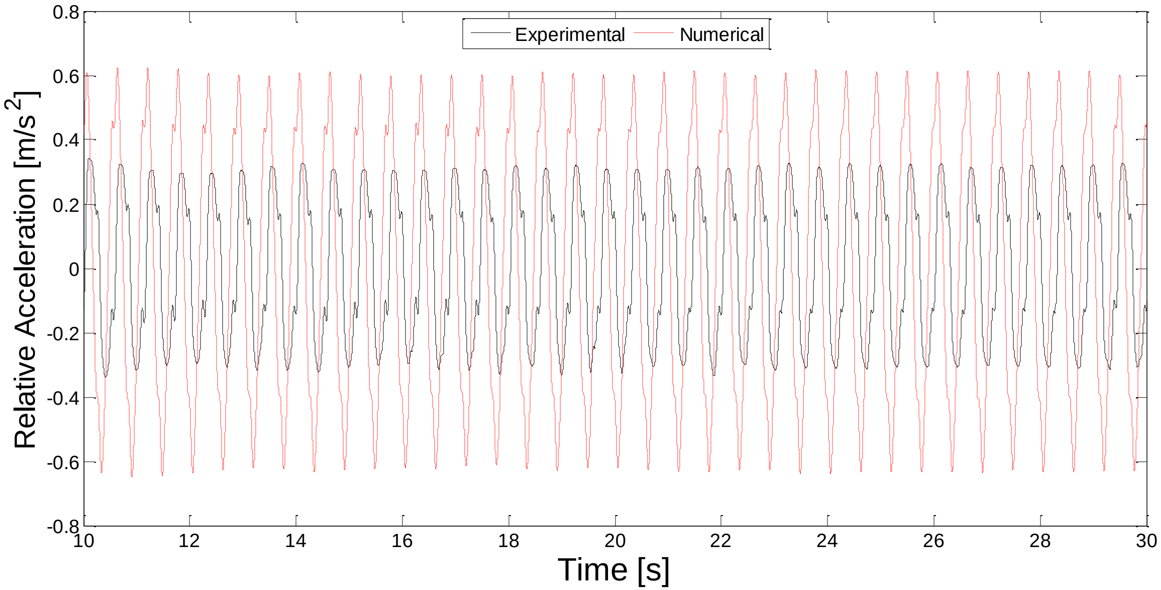
L_v = 4 cm
f_L=1.63Hz

Numerical Vs Experimental results



Sinusoidal test:
f=1.65Hz

L_v = 5 cm



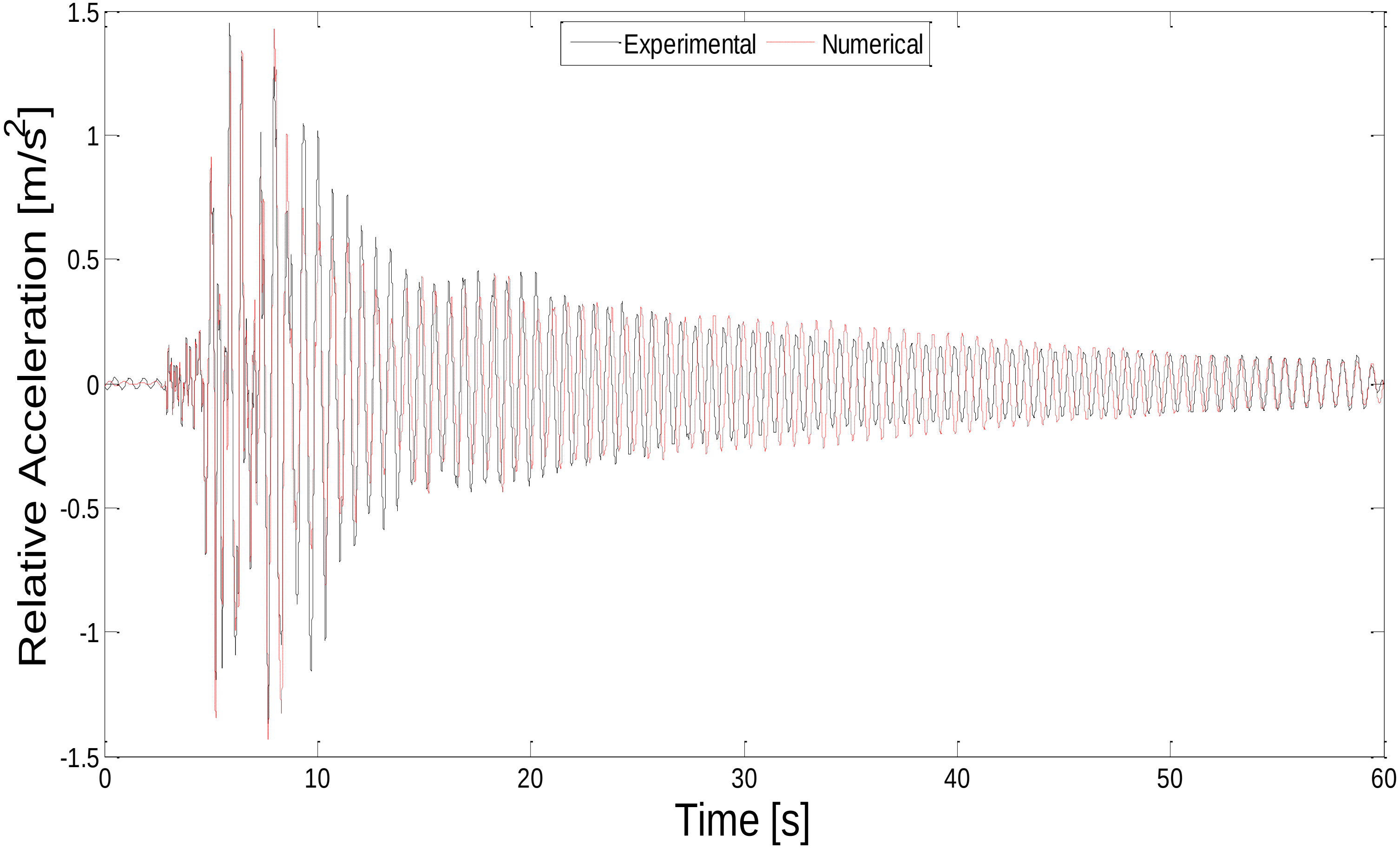
Sinusoidal test:
f=1.75Hz

L_v = 5 cm

Numerical Vs Experimental results

Tolmezzo acceleration

$L_v = 4$ cm



VIRTUAL EXPERIMENT ★

Efficient Experiments allow to build up virtual experiments

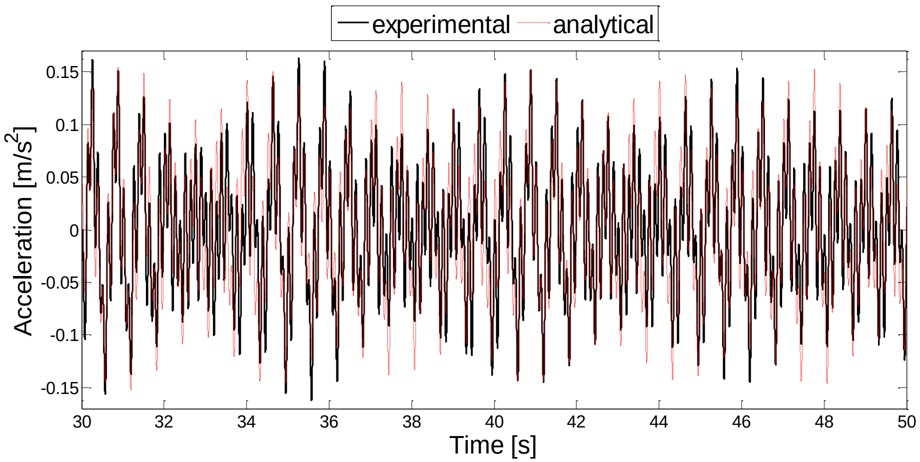
Once a proposed theoretical formulation is reliable
having confirmed efficient tests

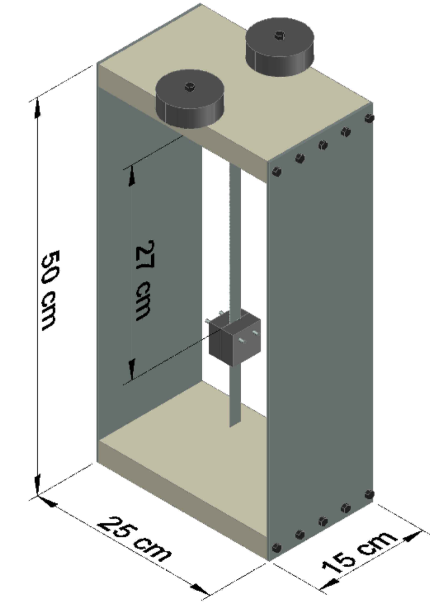
Simulations from this Mathematical formulation
are
virtual experiments

Experimental validation

Sinusoidal test: f=1.60 Hz

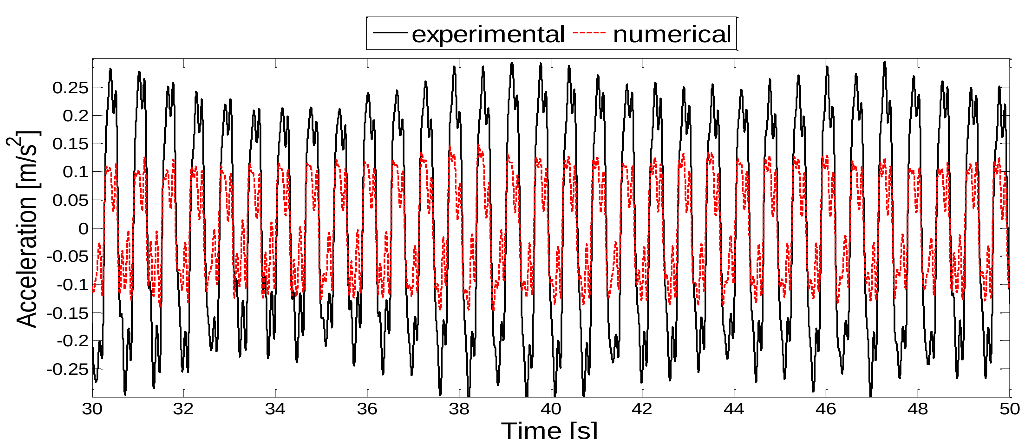
- Numerical-experimental comparison

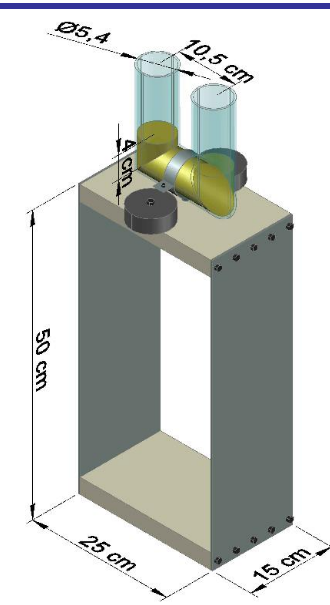




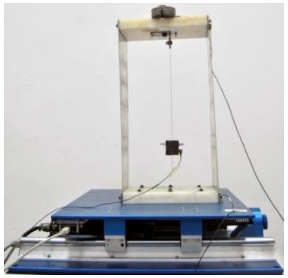
TMD- Virtual Experiment !!!

TLCD- Virtual Experiment ???



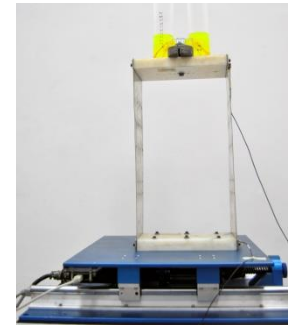


controlled systems:
Numerical-Experimental comparison

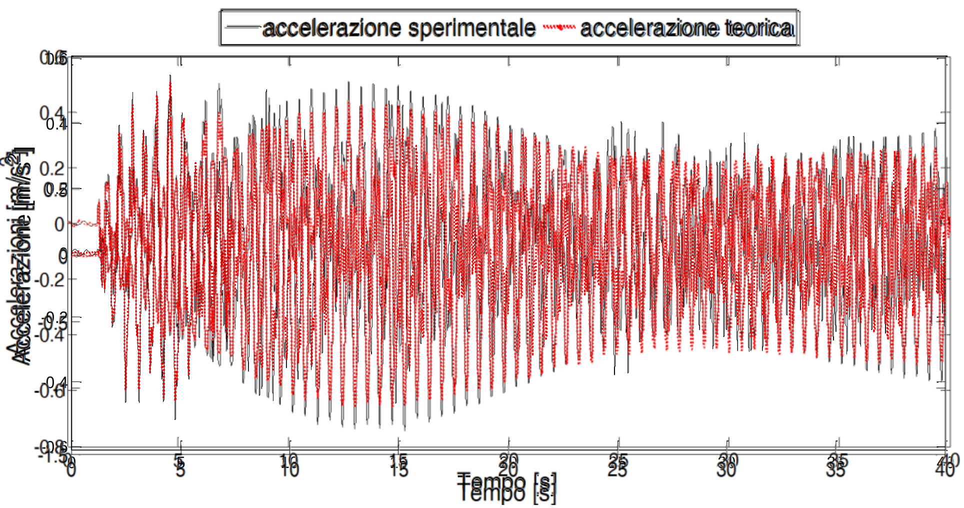


$$\ddot{x}_g = -\Omega^2 x_0 \sin(\Omega t)$$

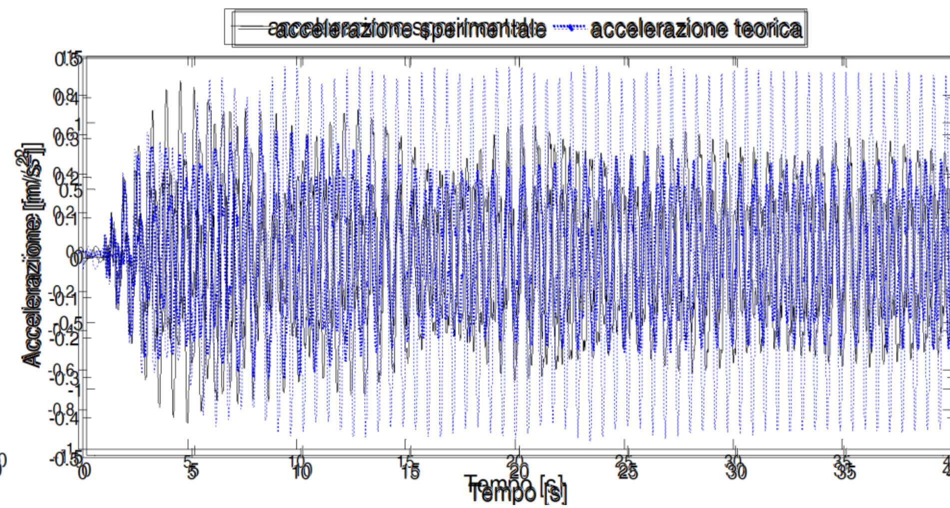
Ω = 1,45 Hz x_o = 0,5 mm



Acceleration response TMD controlled system
Black experimental results
Coloured theoretical results

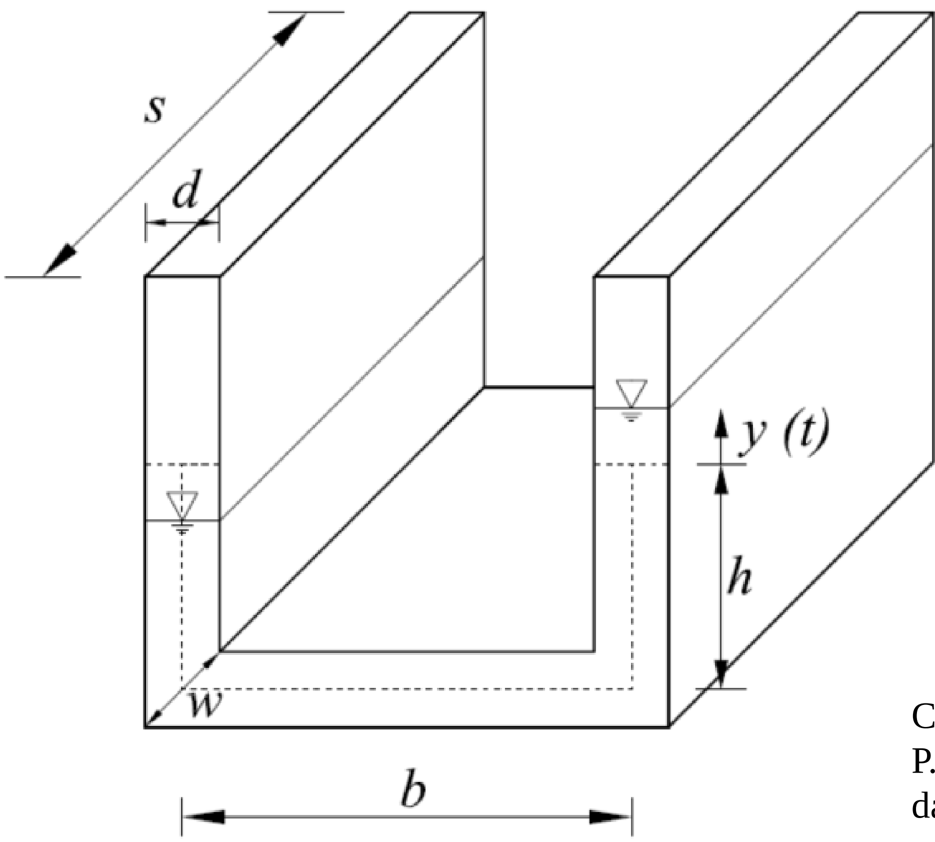


Acceleration response TLCD controlled system
Black experimental results
Coloured theoretical results



WARNING

Experimental validation
of the classical analytical formulation
of a Tuned Liquid Column Damper (TLCD) controlled system



$$w/b$$

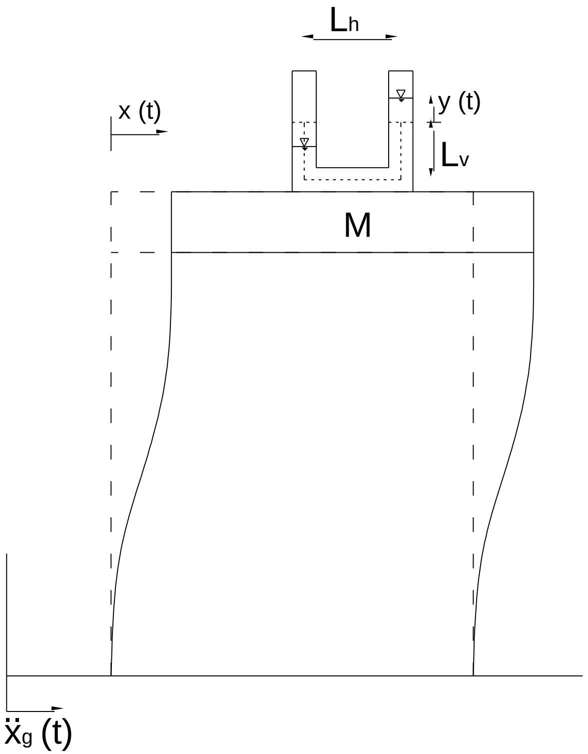
For a small ratio the classical nonlinear mathematical model is proper to predict the surface liquid motion.

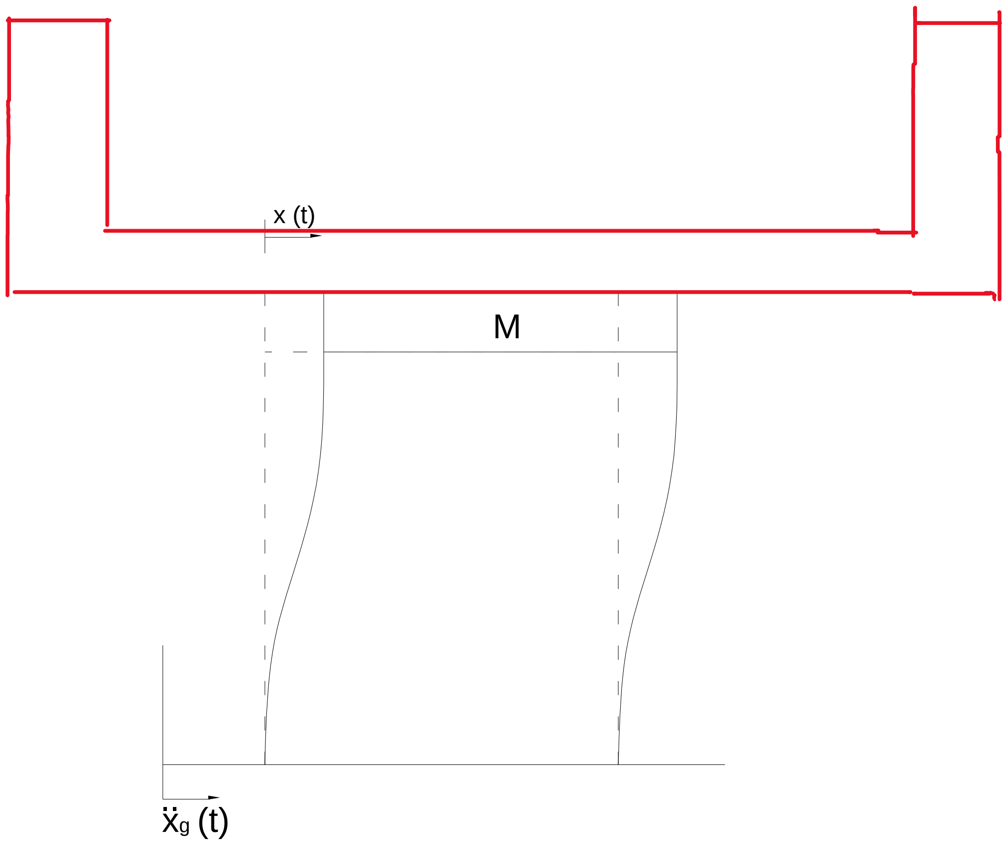
Chaiviriyawong P, Webster WC, Pinkaew T, Lukkunaprasit P. Simulation of characteristics of tuned liquid column damper using a potential-flow method. Eng Struct 2007;29:132–44.

Experimental validation of the classical analytical formulation of a Tuned Liquid Column Damper (TLCD) controlled system

$$w / b$$

Small ratio is not generally appealing for structures since space constraints often limit the TLCD horizontal length





H
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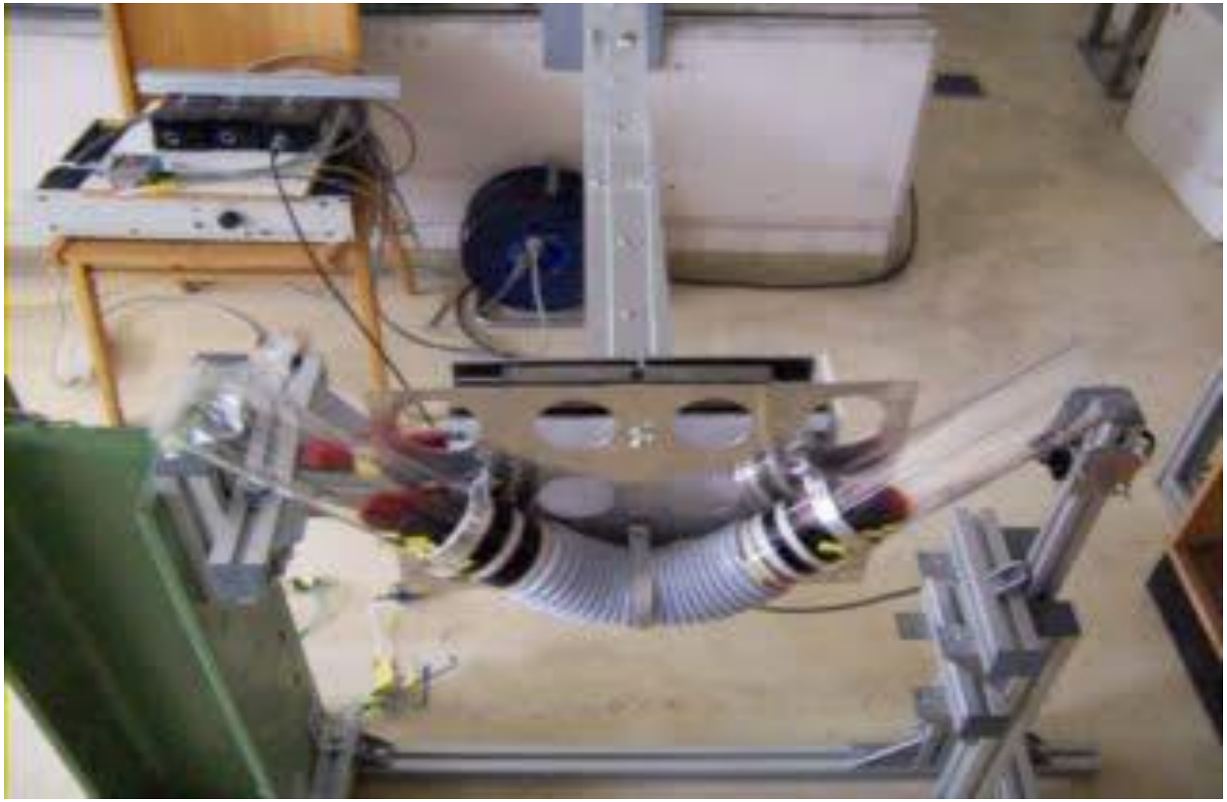
!



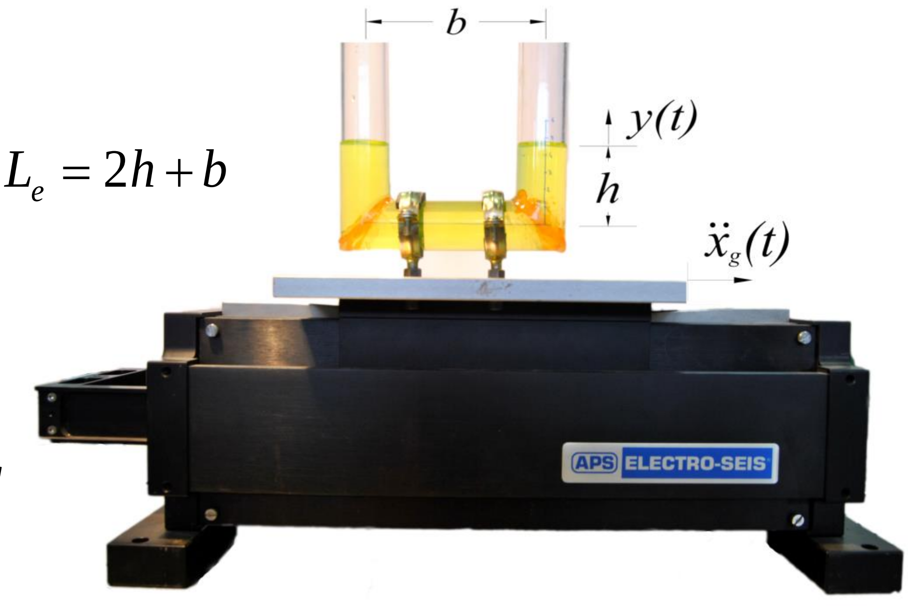
University of Vienna

- ***TLCDs are relatively easy to install in new and existing buildings.***
- ***It is easy to adjust their frequencies and they can be combined with active control mechanism (gas-spring effect).***
- ***The water in the tank can be used for fire fighting (no need to add mass to the structure).***
- ***Installation as well as maintenance cost is comparatively low.***

A step Backward: the device only

The classical analytical formulation

$$L_e = 2h + b$$



$$m_{TLCD}\ddot{y} + \frac{1}{2}\rho A \xi |\dot{y}|\dot{y} + 2\rho A g y = -m_h \ddot{x}_g$$

$$m_{TLCD} = \rho A(b + 2h) = \rho A L_e$$

$$m_h = \rho A b$$

$$\ddot{y}(t) + \frac{1}{2}\frac{\xi}{L_e}|\dot{y}(t)|\dot{y}(t) + \omega_0^2 y(t) = -\frac{b}{L_e}\ddot{x}_g(t) \qquad \omega_0 = \sqrt{\frac{2g}{L_e}}$$

y displacement of the liquid in the vertical columns,

ρ density of the liquid inside the TLCD,

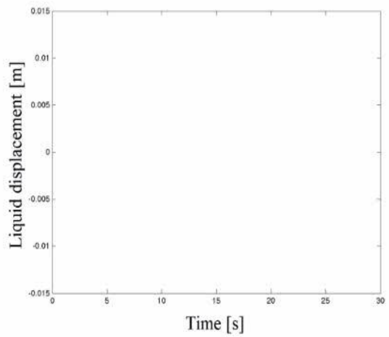
ξ coefficient of head loss

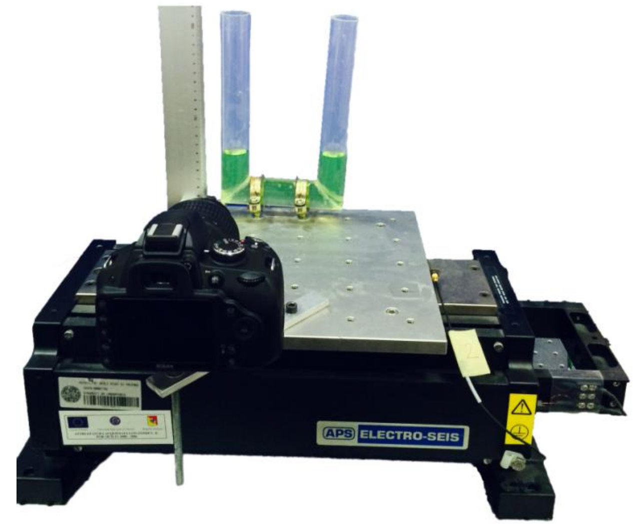
g gravity acceleration

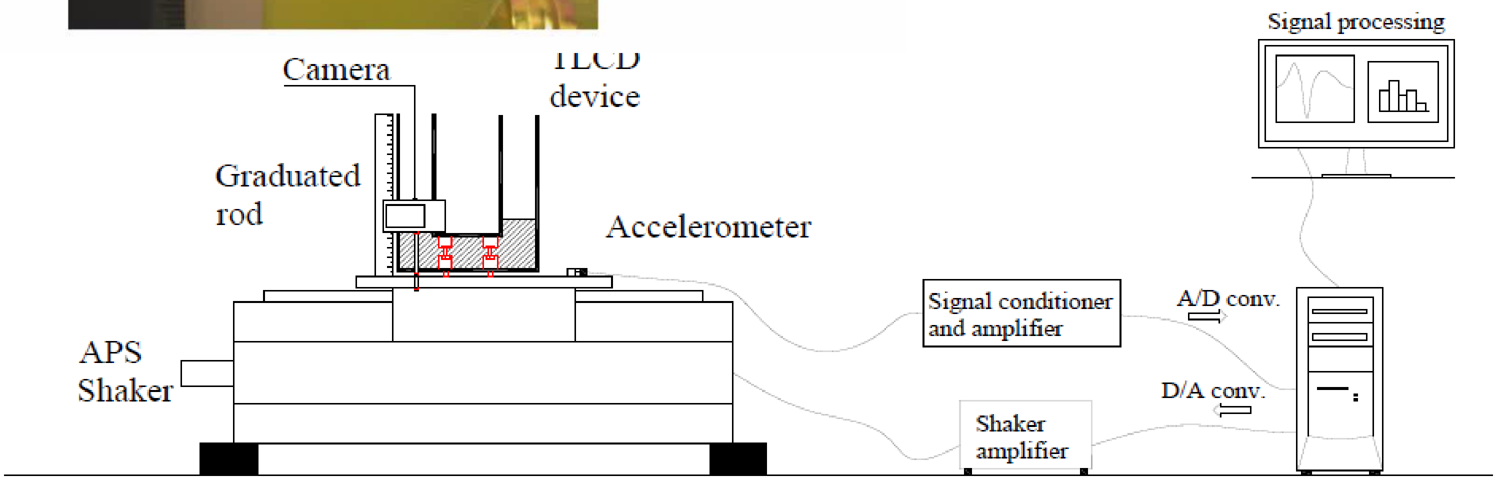
A tube cross section

H. Gao, K.C.S. Kwok, B. Samali, Optimization of tuned liquid column dampers, Eng. Struct., 19 (1997) 476-486.
C.C. Chang, C.T. Hsu, Control performance of liquid column vibration absorbers, Eng. Struct., 20 (1998) 580-586.

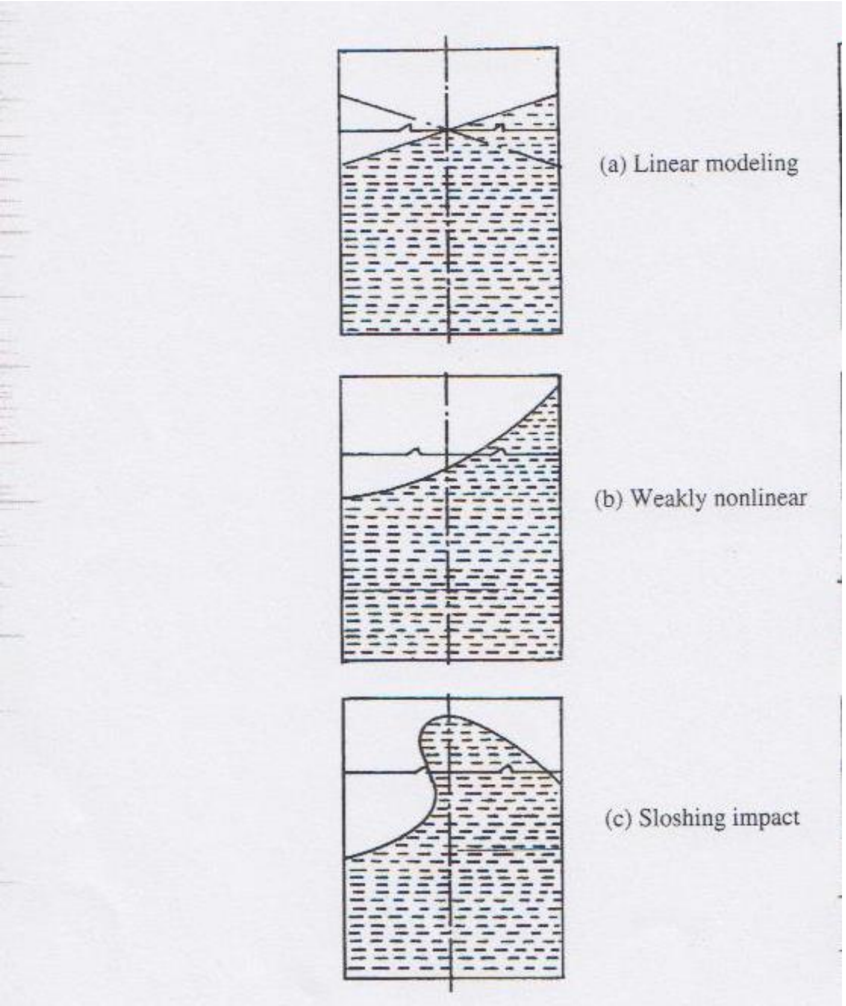
Real dynamics



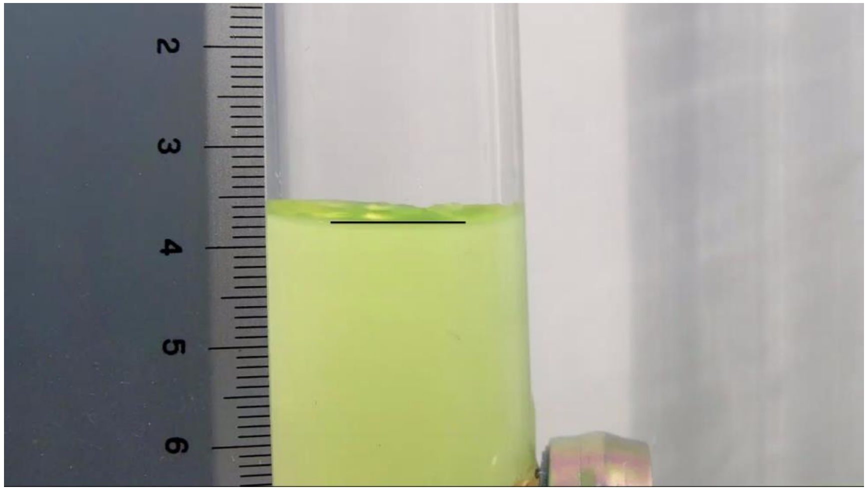


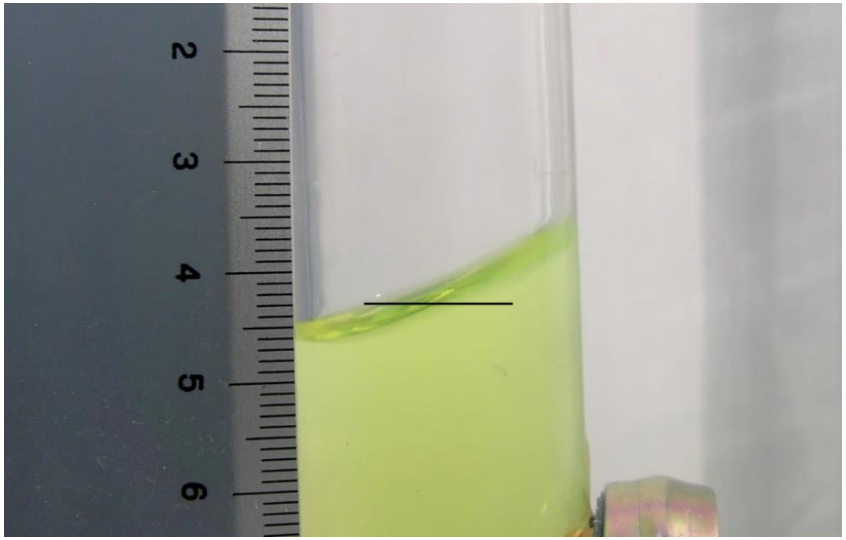


First sloshing mode



Regimes of free-liquid-suface motion





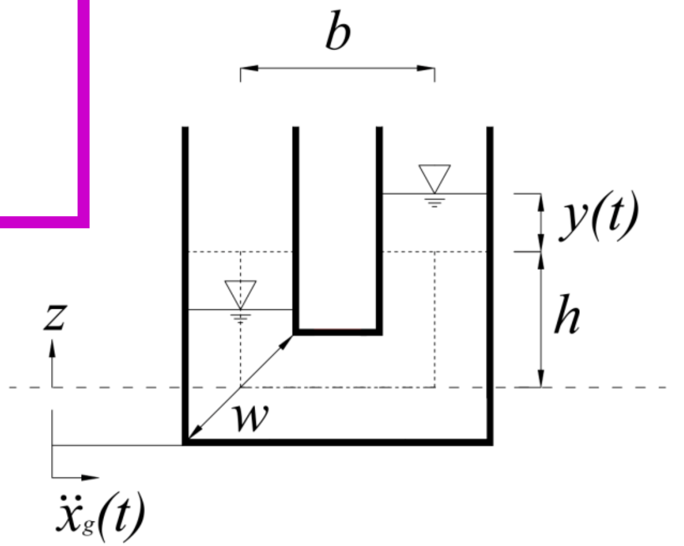
A first attempt to include the sloshing phenomenon, but without considering the simultaneous effect of sloshing and liquid vertical motion.

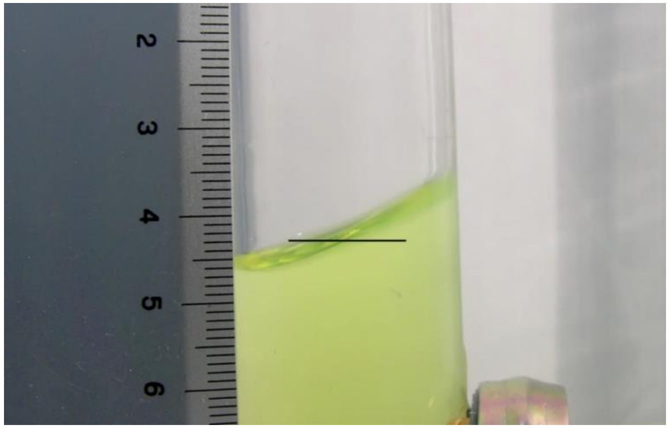
•T. Konar, A. Ghosh, Bimodal vibration control of seismically excited structures by the liquid column vibration absorbers, J. Vib. Control, (2012).

SLOSHING INDUCED VARIATION OF THE FREQUENCY

$$\omega_0 = \sqrt{\frac{2g}{L_e}}$$

$$L_e = 2h + b$$



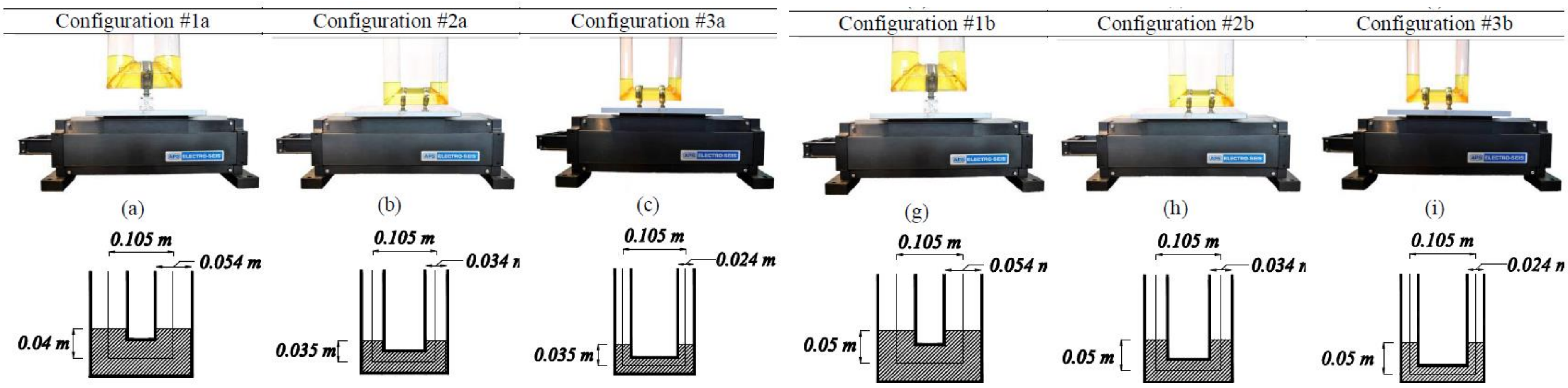


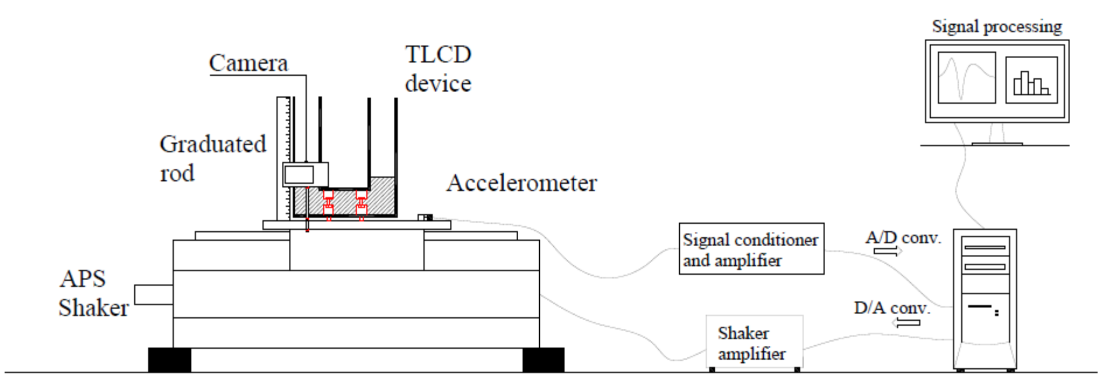
$$\tilde{\omega}_0 = \sqrt{\frac{2g}{\tilde{L}_e}}$$

$$\tilde{L}_e = 2ph + b$$

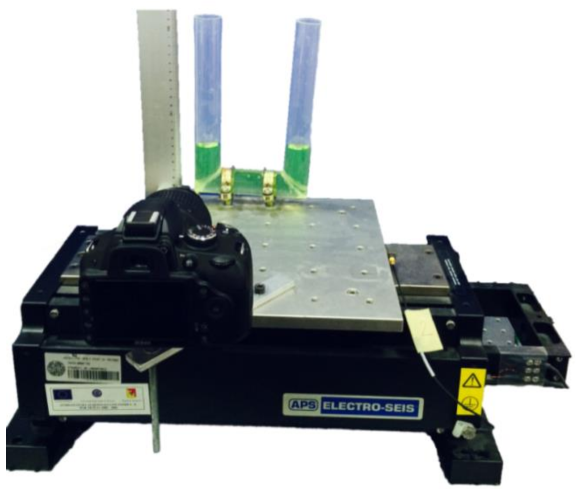
Effective Length; p experimentally determined

Experimental investigation on the TLCD device





Experimental dynamic laboratory (DICAM), Palermo



Innovative Modelling for TLCD Controlled Structures

Innovative Modelling for Capturing Sloshing in TLCD

Nonlinear

$$\ddot{y}(t)+\frac{1}{2}\frac{\xi}{L_e}\left|\dot{y}(t)\right|\dot{y}(t)+\omega_0^2 y(t)=-\frac{b}{L_e}\ddot{x}_g(t)$$

$$\omega_0=\sqrt{\frac{2g}{L_e}}$$

Classical equation of motion

Linear

$$\ddot{y}(t)+\frac{1}{2}\frac{C_\beta}{L_e}\left({}_0^C D_t^\beta y(t)\right)+\omega_0^2 y(t)=-\frac{b}{L_e}\ddot{x}_g(t)$$

Proposed ***linear fractional*** *model*

$${}_0^C D_t^\beta y(t)=\frac{1}{\Gamma(1-\beta)}\int_0^t (t-\tau)^\beta \frac{d}{d\tau}y(\tau)\,d\tau,\quad 0<\beta<1$$

Caputo's Fractional Derivative

$$\mathfrak{I}\left({}_0^C D_t^\beta y(t)\right)=(i\omega)^\beta\,\mathfrak{I}\left(y(t)\right)$$

$$H(\omega)=\frac{-\frac{b}{L_e}}{-\omega^2+\frac{1}{2}\frac{C_\beta}{L_e}(i\omega)^\beta+\omega_0^2}$$

Euler Gamma Function $\Gamma(\beta)=\int_0^\infty e^{-z}z^{\beta-1}dz$ $\quad 0<\beta<1$

$$\beta-1\;!=\Gamma\;\beta$$

fractional calculus

Engineers

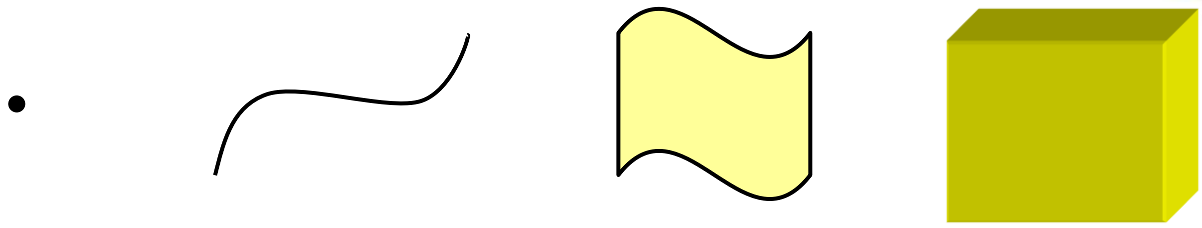
are

Euclidean

People

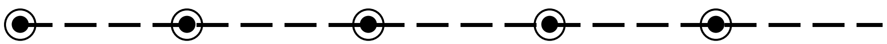
Considering a mechanical model

Engineer are Euclidean People



POINT $[L^0]$ LINE $[L^1]$ SURFACE $[L^2]$ VOLUME $[L^3]$

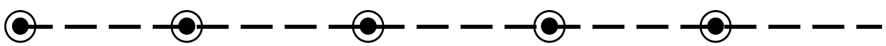
DIMENSIONS



0 VOID 1 VOID 2 VOID 3 VOID 4

DERIVATIVES

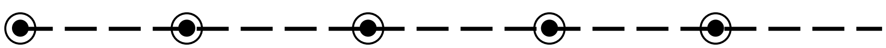
$$d^j f / dx^j = (D^j f)(x)$$



0 VOID 1 VOID 2 VOID 3 VOID 4

PRIMITIVES

$$\int\int\int f(x)...dx = (I^j f)(x)$$



0 VOID 1 VOID 2 VOID 3 VOID 4

Fractional Calculus

Fractional Calculus was born in 1695

De l'Hopital asked Leibniz

- Background

What if the order of the derivative is $\frac{1}{2}$..?

It will lead to a paradox from which one day useful consequences will be drawn.

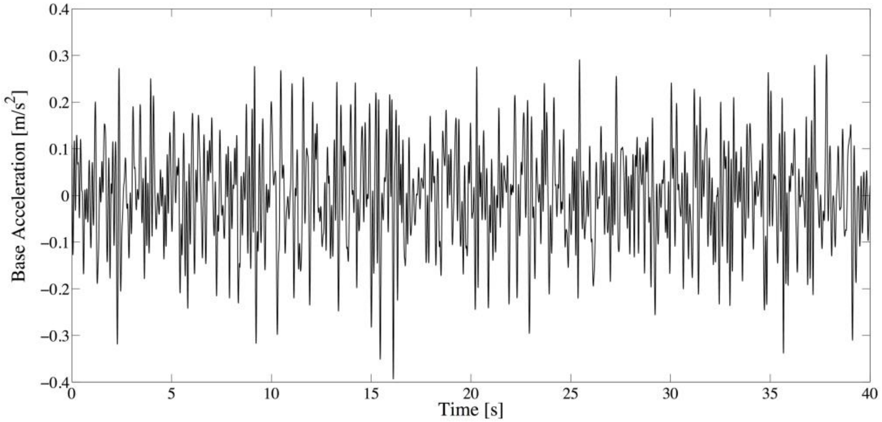
G. De l' Hopital
(1661-1704)

G. Leibniz
(1646-1716)

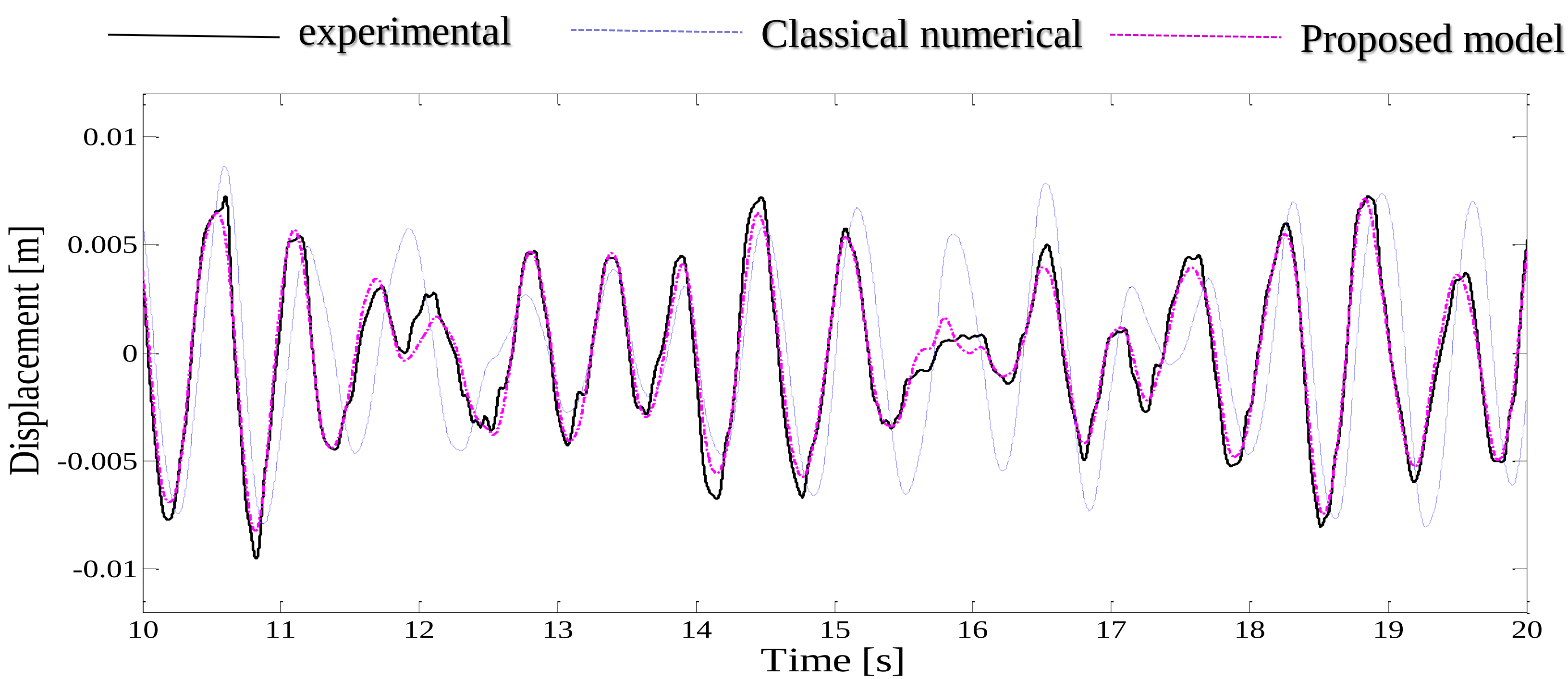
Fractional Calculus Diverse Impact

- *Materials Science*
- *Theoretical Physics*
- *Financial Mathematics*
- …

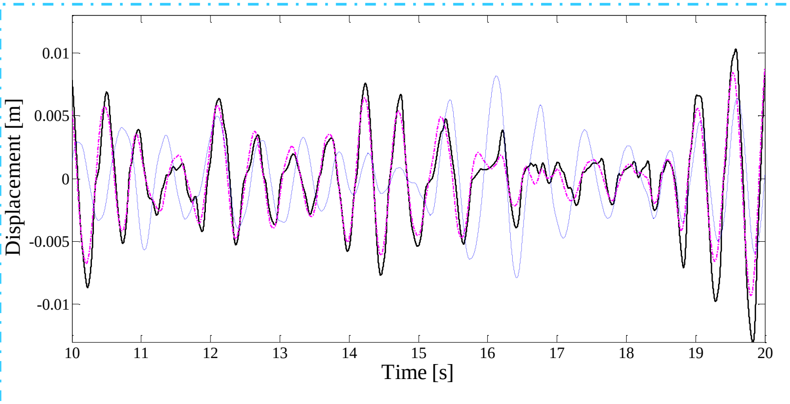
Numerical Vs Experimental results



Broadband noise 0.5-10Hz



The TLCD device:
Numerical-experimental comparison



$\beta = 0.2$

$C_\beta = 7.4$

<u>Ref.: Di Matteo A., Lo Iacono F., Navarra G., Pirrotta A., 2015, Comm. in Nonlinear Science and Numerical Simulation, 23 (229-244)</u>

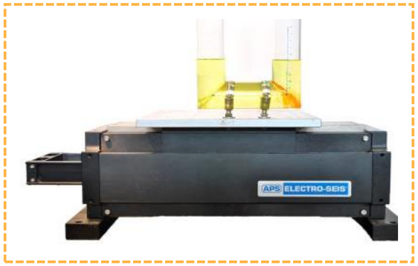
Experimental

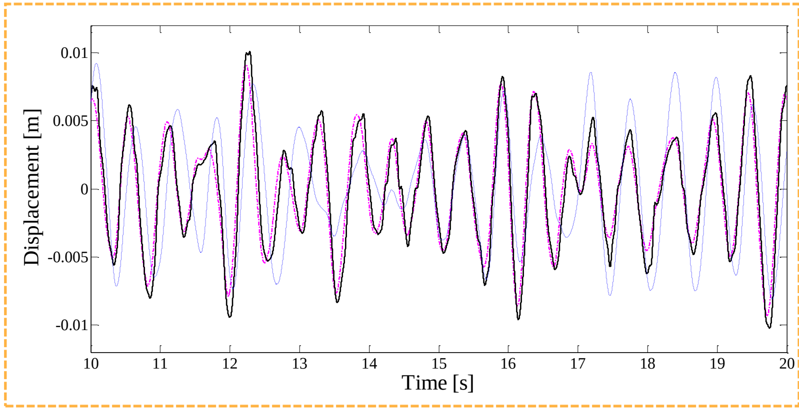
Classical numerical

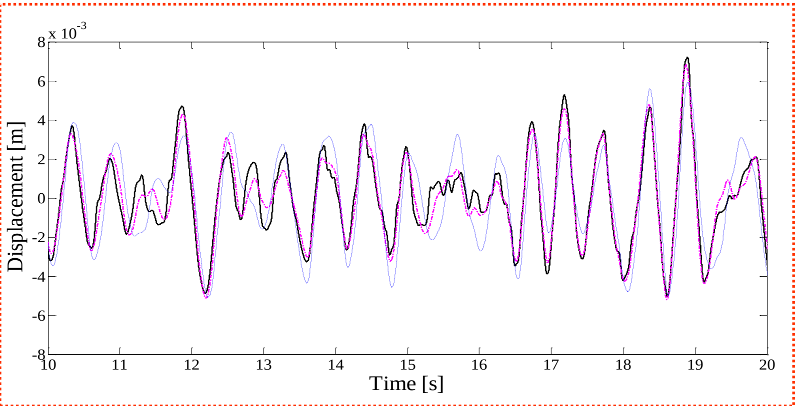
Proposed fractional model

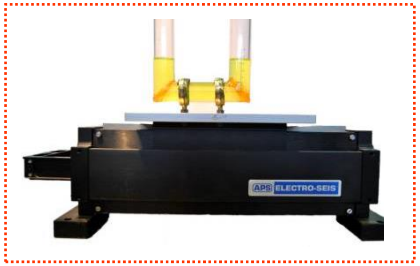
$\beta = 0.4$

$C_\beta = 3.6$









Broadband noise 0.5-10Hz
20 Samples of 25s

$\beta = 0.6$

$C_\beta = 2.1$

TLCD controlled system:
Proposed model with fractional derivative

Classical equation of motion

$$\begin{cases} \left(M+m_{TLCD}\right)\ddot{x}+m_h\ddot{y}+C\dot{x}+Kx=-\left(M+m_{TLCD}\right)\ddot{x}_g \\ m_h\ddot{x}+m_{TLCD}\ddot{y}+\frac{1}{2}\rho A\xi\left|\dot{y}\right|\dot{y}+2\rho Agy=-m_h\ddot{x}_g \end{cases}$$

M, C, K

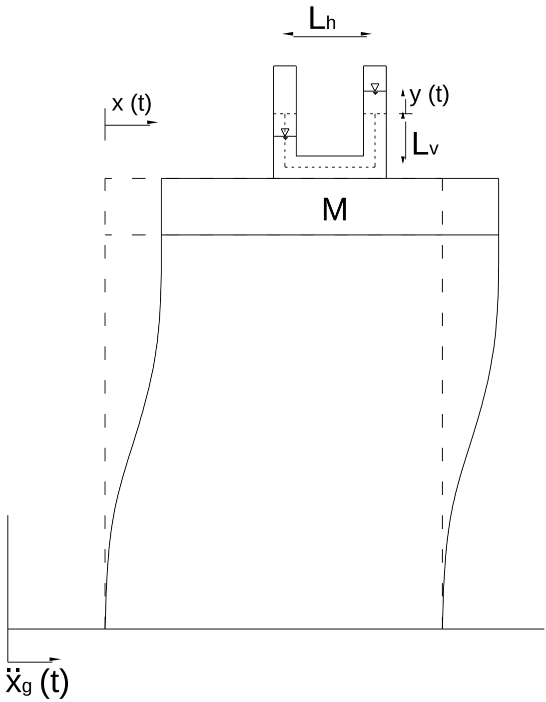
Main system parameters

$$m_{TLCD}=\rho A\left(L_h+2L_v\right)=\rho AL$$

$$m_h=\rho AL_h$$

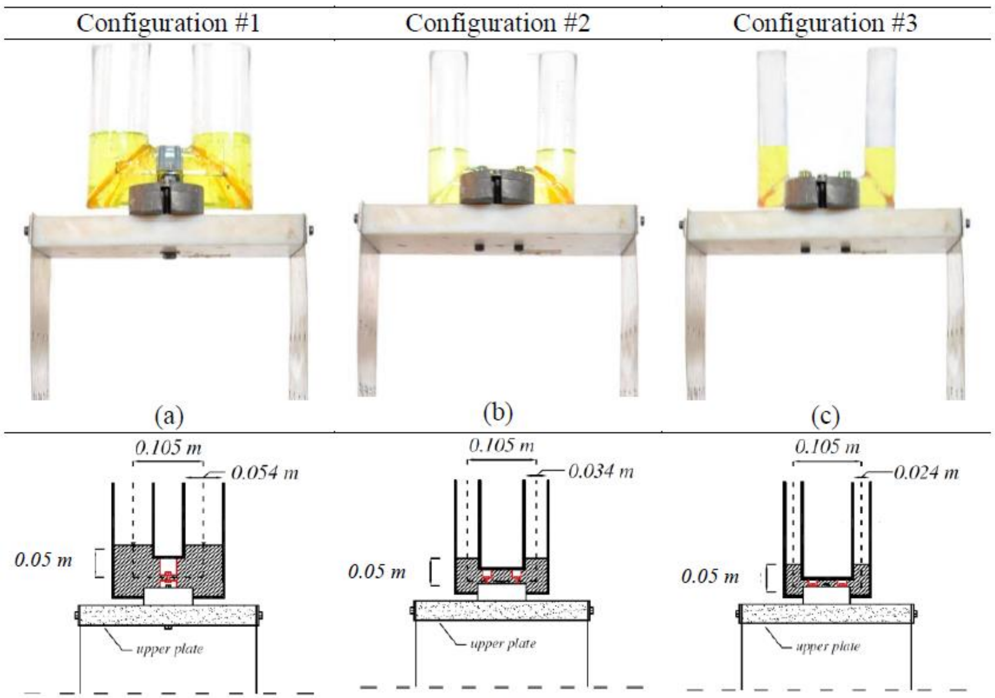
Proposed linear fractional model

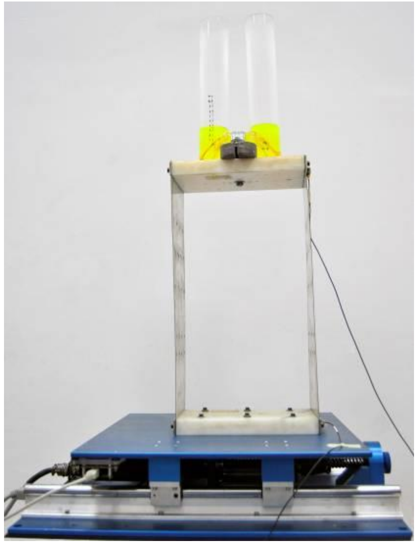
$$\begin{cases} \left(M+m_{TLCD}\right)\ddot{x}+m_h\ddot{y}+C\dot{x}+Kx=-\left(M+m_{TLCD}\right)\ddot{x}_g \\ m_h\ddot{x}+m_{TLCD}\ddot{y}+\frac{1}{2}\rho AC_\beta\left({}_0^C D_t^\beta y(t)\right)+2\rho Agy=-m_h\ddot{x}_g \end{cases}$$



Ref.: Di Matteo A., Di Paola M., Pirrotta A.; Innovative modeling of Tuned Liquid Column Damper controlled structures, 2015, Smart Structures and Systems, Submitted.

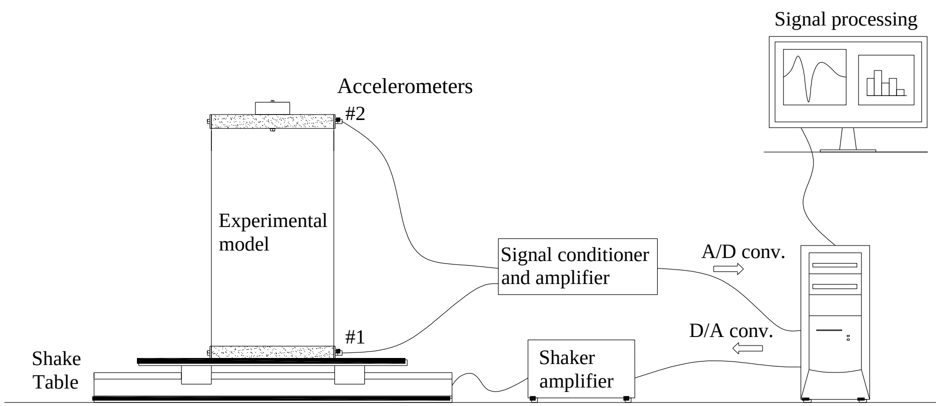
TLCD controlled system:
Experimental validation of the proposed model



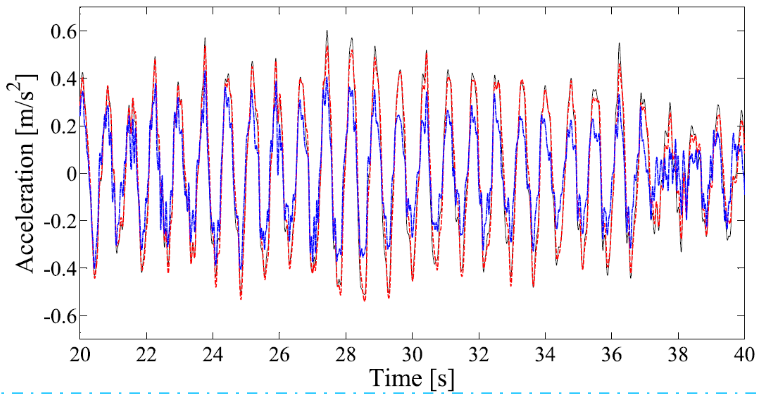


Experimental dynamic laboratory (DICAM), Palermo

	Configuration #1	Configuration #2	Configuration #3
M	4.486 kg	4.226 kg	4.208 kg
ζ_1	0.005	0.0032	0.0037
ω_1	9.10 rad/s	9.54 rad/s	9.65 rad/s
L	0.205 m	0.205 m	0.205 m
ω_2	9.78 rad/s	9.78 rad/s	9.78 rad/s
ω_{exp}	11.31 rad/s	10.81 rad/s	10.56 rad/s
ξ	6	8	15



TLCD controlled system:
Numerical-Experimental comparison (time domain)



$\beta = 0.15$

$C_\beta = 9.9$

Experimental

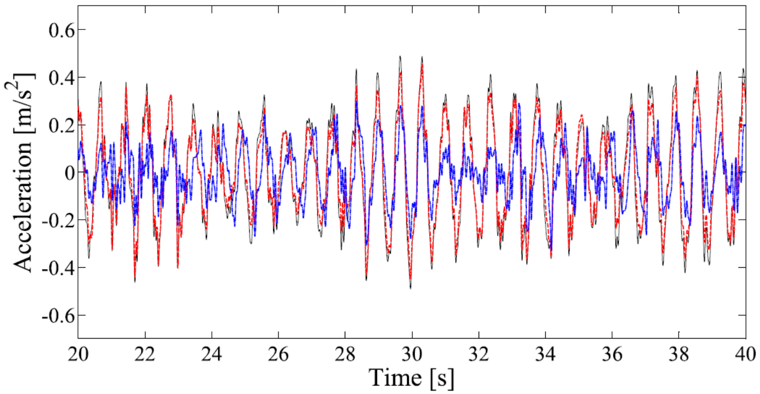
Classical numerical

Proposed fractional model

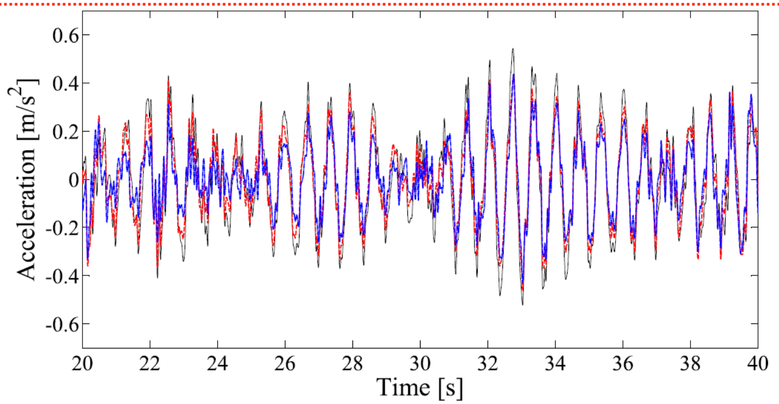
Broadband noise 0.5-10Hz
10 Samples of 60s

$\beta = 0.4$

$C_\beta = 3.6$



Experimental dynamic laboratory (DICAM), Palermo

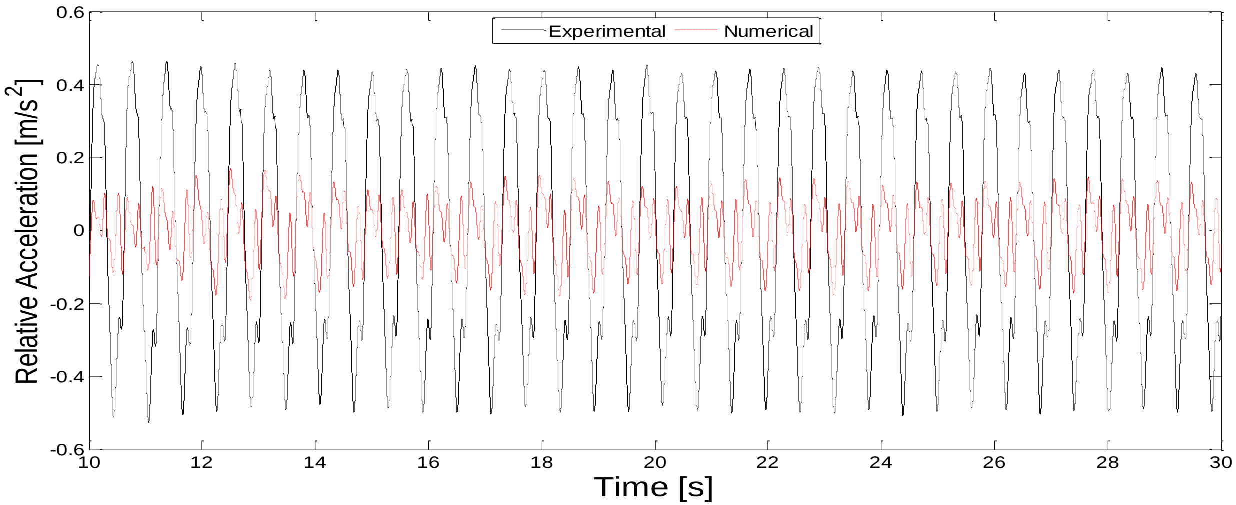


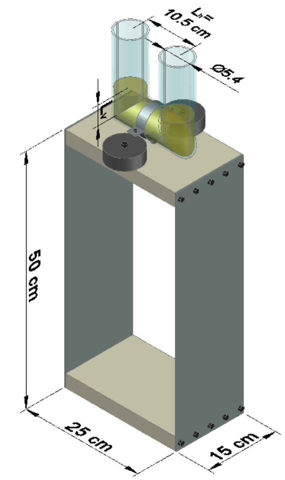
$\beta = 0.6$

$C_\beta = 2.1$

Ref.: Di Matteo A., Di Paola M., Pirrotta A.: Innovative modeling of Tuned Liquid Column Damper controlled structures, 2015, Smart Structures and Systems, Submitted.

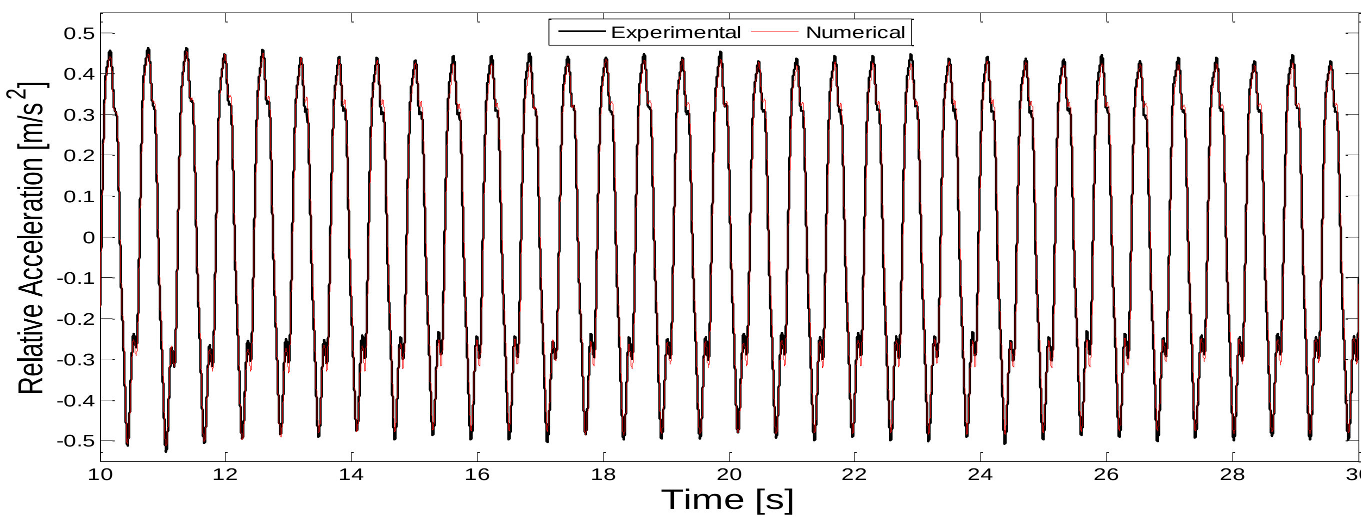
Numerical Vs Experimental results





L_v= 4 cm;

Sinusoidal test:
f=1.65Hz

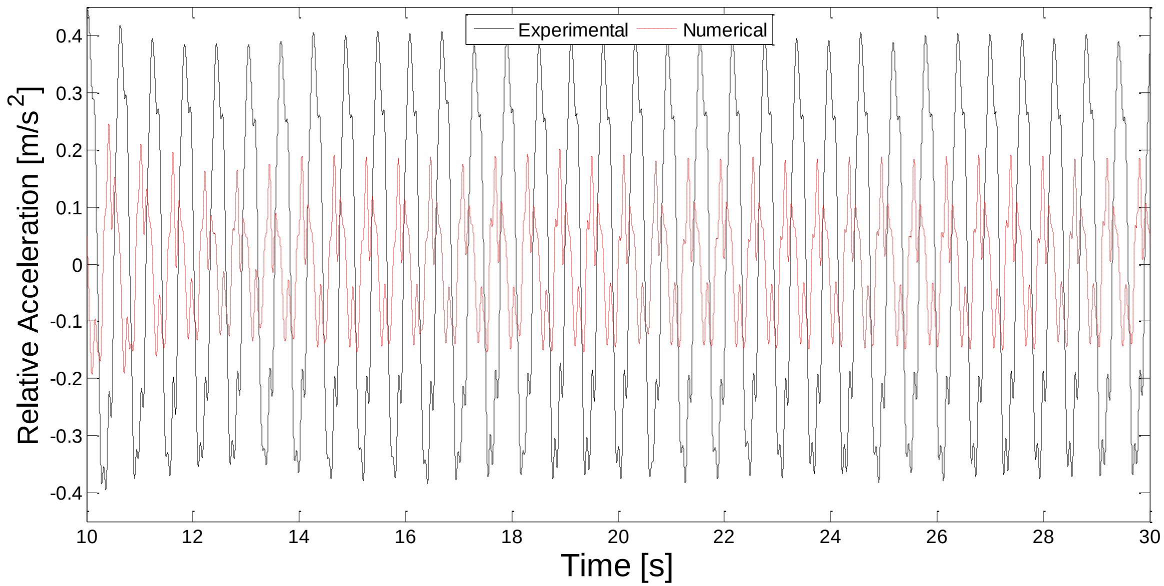


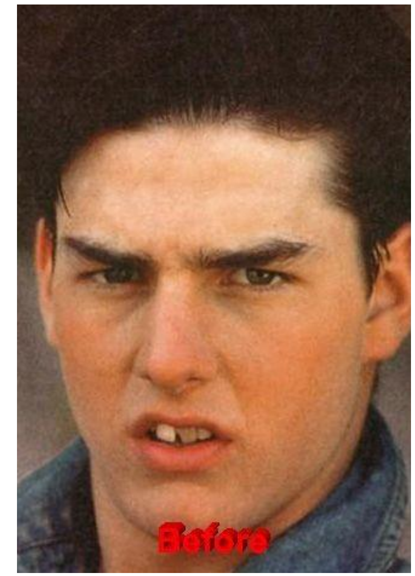
- With fractional term

Numerical Vs Experimental results

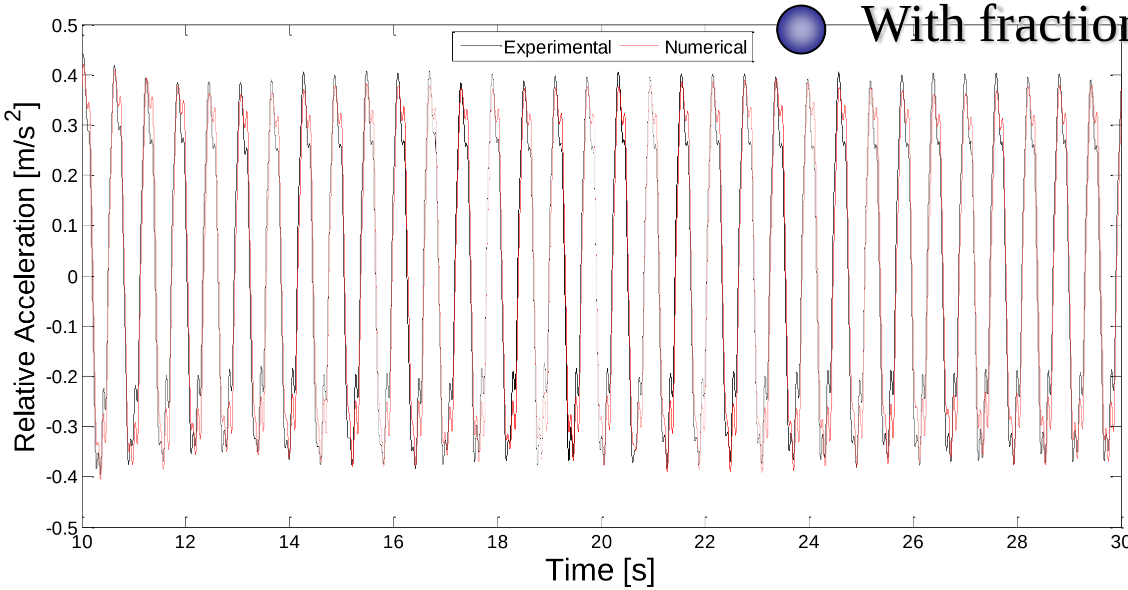
Sinusoidal test: f=1.65Hz

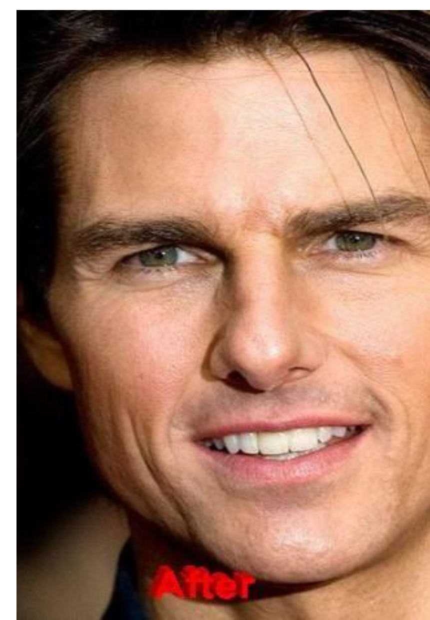
L_v = 5 cm



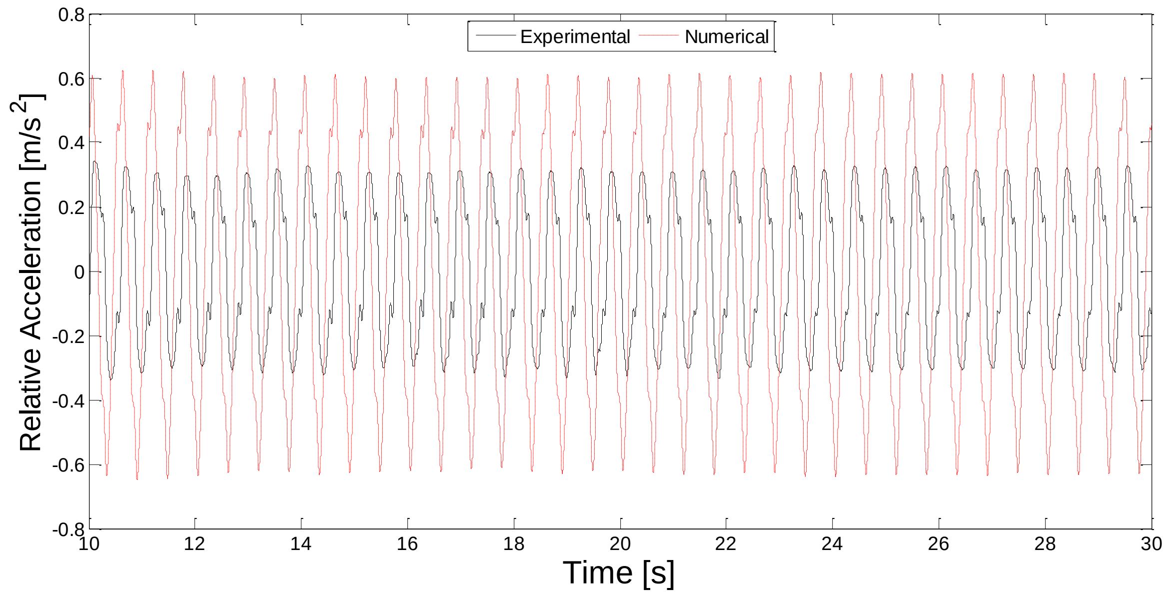


With fractional term



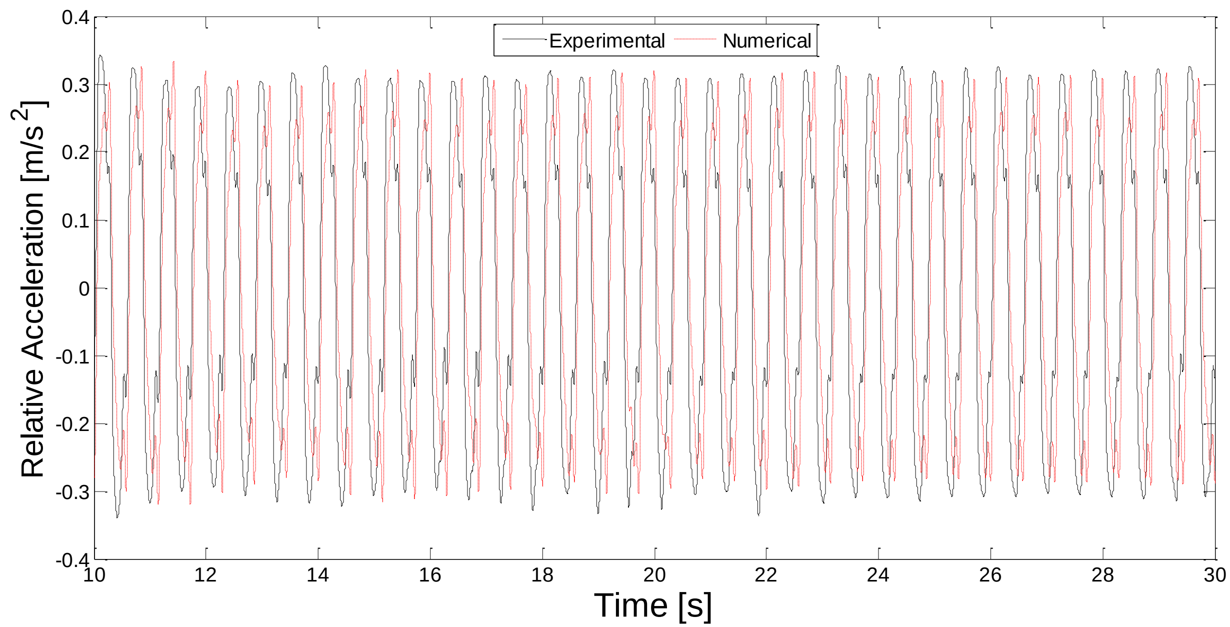


Numerical **Vs** Experimental results



Sinusoidal test:
f=1.75Hz

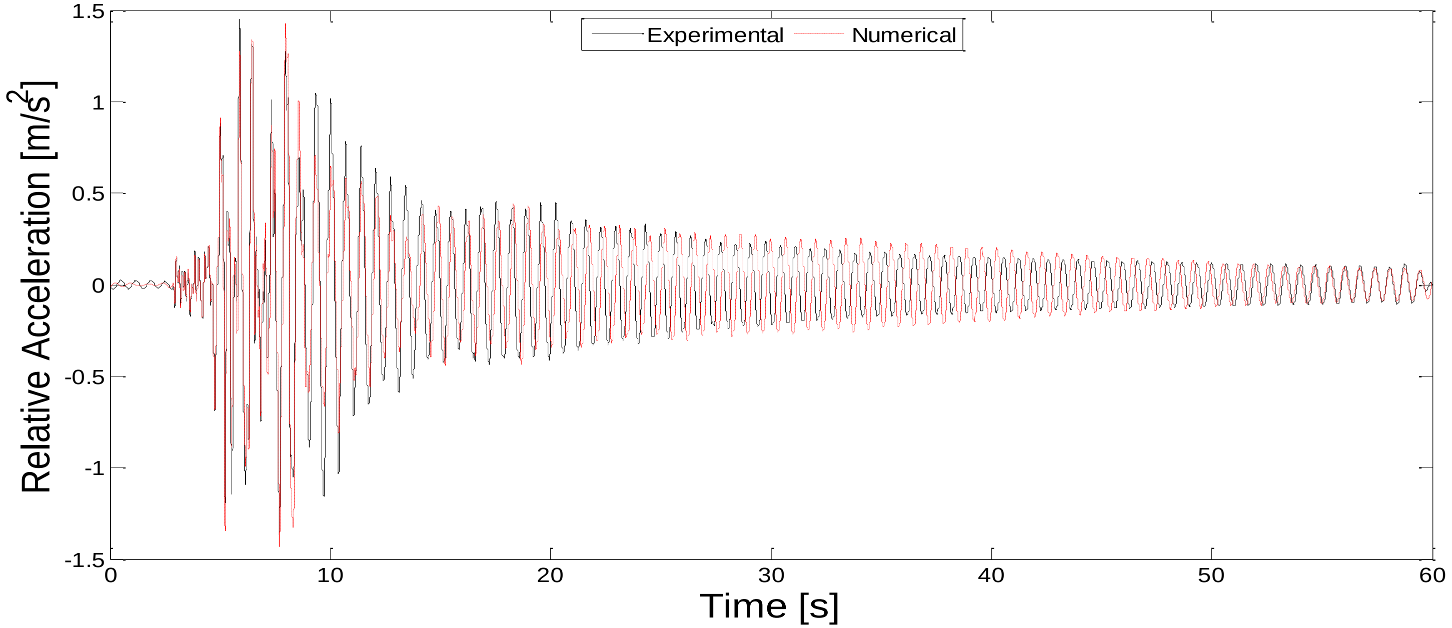
L_v = 5 cm



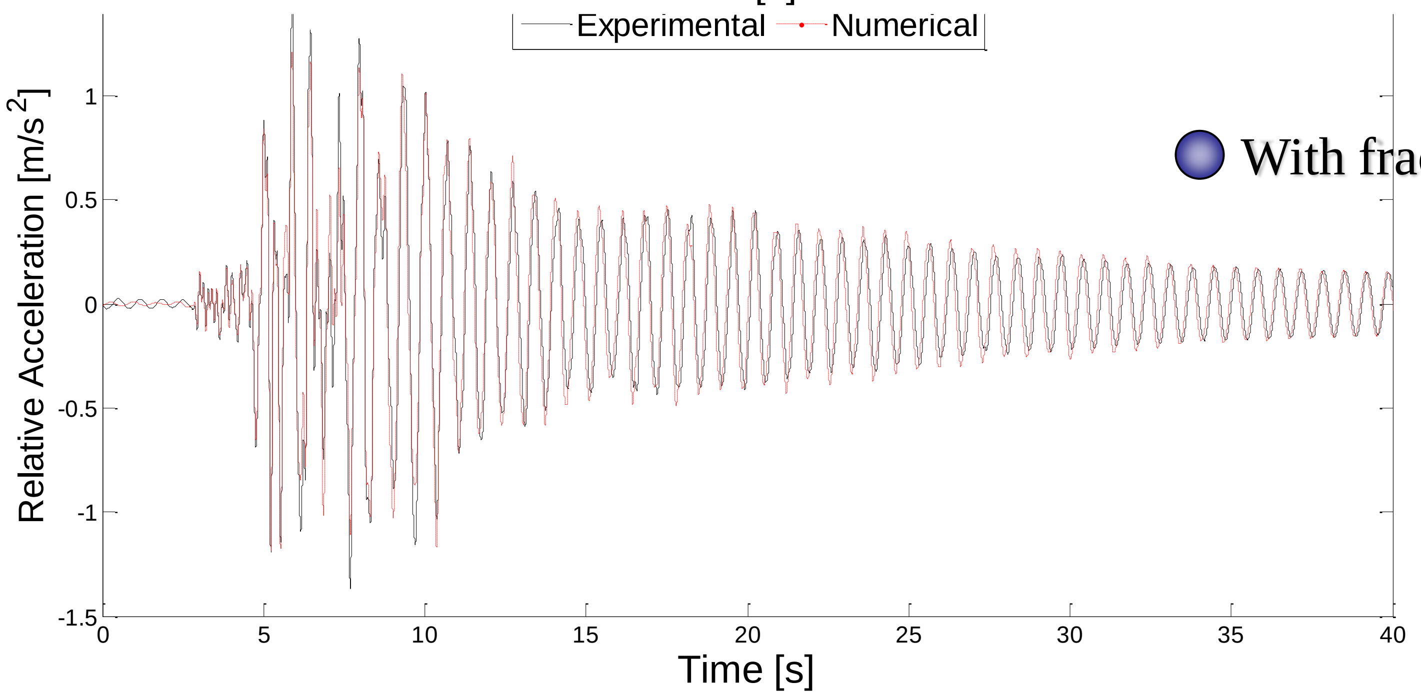
- With fractional term

Numerical Vs Experimental results

Tolmezzo acceleration

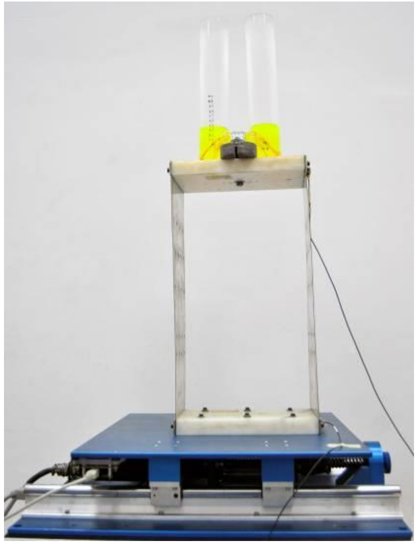


L_v = 4 cm



With fractional term

WE HAVE A Virtual Experiment!!!!



$$\begin{cases} \left(M + m_{TLCD}\right)\ddot{x} + m_h \ddot{y} + C\dot{x} + Kx = -\left(M + m_{TLCD}\right)\ddot{x}_g \\ m_h \ddot{x} + m_{TLCD}\ddot{y} + \frac{1}{2}\rho A C_\beta \left({}_0^C D_t^\beta y(t)\right) + 2\rho A g y = -m_h \ddot{x}_g \end{cases}$$

Concluding Remarks

- Experimental Tests makes the difference between mathematical method and scientific method.

  It is not easy performing tests especially for validating novel theoretical model!

- However , refining a theoretical model through tests, then allow you to have virtual experiments leading to tremendous cost savings and improved quality!

- The classical analytical formulation for TLCD allow us to predict the effectiveness of the control but, in some cases, it is not able to provide a good experimental-numerical agreement;

- An alternative formulation has been proposed to better match the experimental results then to be proposed as virtual experiment;